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BRLSC: AN ADVANCED EULERIAN CODE FOR PREDICTING SHAPED CHARGES, VOLUME I

Prepared by

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The BRLSC code is a modified version of the HELP code developed for the purpose of predicting phenomena associated with the performance of shaped charges. During the process of modifying HELP to enable it to handle shaped charge problems, a number of additions and changes were introduced. The resulting differences between HELP and BRLSC fall into two basic categories. The first category includes the necessary additions to enable the code to generate shaped charge problems, treat explosives, simulate a slip surface

between the liner and the explosive, and insure realistic jet formation. These additions were specifically required by the shaped charge application. The second category consists of changes made to improve the way in which free surface cells are handled, to allow the thin liner to move through the grid without becoming distorted, to increase the reliability and stability of calculations, and to decrease the cost of running problems. As the result of these additions and changes, most of the subroutines in BRLSC have been changed substantially from the original HELP version. However, since most of the logic involved is similar to that employed in HELP, users familiar with HELP should have no difficulties with BRLSC.

ACKNOWLEDGEMENT

The author is grateful to Laura Jean Hageman for supplying the original HELP program from which the shaped charge program herein reported was developed, and to Dr. J. M. Walsh, Dr. R. T. Sedgwick and Miss Hageman for providing much technical guidance and assistance during the course of the present investigation. The present report is written in the same format as the HELP[1] documentation, and portions of that report are included herein for the sake of completeness and convenience to the prospective user.

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I. INTRODUCTION

The BRLSC code is a modified version of the HELP code and was developed under Contract DAAD 05-70-C-0275[2] to the U. S. Army Ballistics Research Laboratory for the purpose of predicting phenomena associated with the performance of shaped charges. During the process of modifying HELP to enable it to handle shaped charge problems, a number of additions and changes were introduced. The resulting differences between HELP and BRLSC fall into two basic categories. The first category includes the necessary additions to enable the code to generate shaped charge problems, treat explosives, simulate a slip surface between the liner and the explosive, and insure realistic jet formation. These additions were specifically required by the shaped charge application. The second category consists of changes made to improve the way in which free surface cells are handled, to allow the thin liner to move through the grid without becoming distorted, to increase the reliability and stability of calculations, and to decrease the cost of running problems. As the result of these additions and changes, most of the subroutines in BRLSC have been changed substantially from the original HELP version. However, since most of the logic involved is similar to that employed in HELP, users familiar with HELP should have no difficulties with BRLSC.

It is the purpose of the present document (Volumes I and II) to report the BRLSC program in detail for potential users. A companion report to this one, by R.T. Sedgwick, J.M. Walsh, and the present author, gives a general discussion of the shaped charge problem and computed results for three specific cases.

In Section II of this report a general description of the numerical method is presented. Section III deals with the elastic-plastic constitutive relations. In Section IV, the method used to propagate tracer particles is described and the way in which these particles are used is explained in detail. Section V describes the pressure iteration scheme used in determining the pressures in cells containing more than one material. In Section VI the method used to apply a pressure boundary condition is described. (By using this pressure boundary condition, an effective slip surface is introduced.) Section VII describes several sample calculations which have been run with BRLSC. Finally, Section VIII is a users guide and provides a brief description of every subroutine, detailed instructions for generating and restarting problems, and a dictionary of important variables. In Volume II of this report, a complete listing of the BRLSC FORTRAN program is provided.

II. GENERAL DESCRIPTION OF THE NUMERICAL METHOD

In the present section the conservation equations and the numerical model used to treat these equations are presented. In addition the equations of state used to model both the condensed inert material and the explosives are presented, along with the necessary equation-of-state parameters for ten liner materials and eighteen explosives.

2.1 CONSERVATION EQUATIONS

Space is divided into fixed Eulerian cells through which the fluid moves. To arrive at expressions for the rate of change of total mass, momentum and energy within such a cell, it is convenient to start with the equations of motion in the form:

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x_i} \left(\rho u_i \right) \tag{1}$$

$$\rho \frac{Du_j}{Dt} = \frac{\partial}{\partial x_i} \left(\sigma_{ij} \right) \tag{2}$$

$$\rho \frac{DE_T}{Dt} = \frac{\partial}{\partial x_i} \left(\sigma_{ij} u_j \right) \tag{3}$$

Here the σ_{ij} are the components of the stress tensor, which can be regarded as the sum of the hydrostatic pressure, $-\delta_{ij}P$, and the deviatoric stress component, s_{ij}, i.e.,

$$\sigma_{ij} = s_{ij} - \delta_{ij}P \tag{4}$$

and E_T is the total energy (kinetic plus internal) per unit mass. Tensor notation is implied, so that repeated indices denote summation.

Expanding the convective derivatives in Eqs. (2) and (3), $Df/Dt = \partial f/\partial t + u_i \, \partial f/\partial x_i$, then adding Eq. (1) times u_j to Eq. (2), and Eq. (1) times E_T to Eq. (3), and collecting terms, gives

$$\frac{\partial}{\partial t}\left(\rho u_j\right) = \frac{\partial}{\partial x_i}\sigma_{ij} - \frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) \tag{5}$$

$$\frac{\partial}{\partial t}\left(\rho E_T\right) = \frac{\partial}{\partial x_i}\left(\sigma_{ij} u_j\right) - \frac{\partial}{\partial x_i}\left(\rho u_i E_T\right) . \tag{6}$$

For the developments to follow it is desirable to replace these differential equations by the analogous integral equations, obtained by integrating over the cell volume, V, and then converting the volume integral of divergences to surface integrals over the cell surfaces. Equations (1), (5), and (6) then become

$$\frac{\partial}{\partial t}\int_V \rho dV = -\int_s \rho u_i n_i ds \tag{7}$$

$$\frac{\partial}{\partial t}\int_V \rho u_j dV = \int_s \sigma_{ij} n_i ds - \int_s \rho u_i u_j n_i d_s \tag{8}$$

$$\frac{\partial}{\partial t}\int_V \rho E_T dV = \int_s \sigma_{ij} u_j n_i ds - \int_s \rho u_i E_T n_i ds . \tag{9}$$

2.2 DIFFERENCE EQUATIONS

2.2.1 Division into Phases

It is convenient to express the integral conservation relations, Eqs. (7) through (9), as finite difference equations over the time step Δt and also to decompose the total stress σ_{ij} into its deviator and hydrostatic components, according to Eq. (4). This gives, for the increments of total mass (m), momenta (mu_j) and energy (mE_T) within the cell

$$\Delta m = \qquad\qquad - \Delta t \int_s \rho u_i n_i ds \tag{10}$$

$$\Delta(mu_j) = - \Delta t \int_s (\delta_{ij} P - S_{ij}) n_i ds \qquad - \Delta t \int_s (\rho u_i u_j) n_i ds \tag{11}$$

$$\Delta(mE_T) = - \Delta t \int_s (\delta_{ij} P - S_{ij}) u_j n_i ds \qquad - \Delta t \int_s (\rho u_i E_T) n_i ds \tag{12}$$

Here, the terms on the right are divided into increments due to pressure and stress deviator forces on the cell surface (first colume), and the increments (second column) due to the transports of mass, momentum or energy through the surface of the cell. These two types of contributions are accounted for in the computation in distinct phases. Specifically, during each time step all cells are updated for:

- Pressure and deviator stress effects in Phase 1
- Transport effects in Phase 2

Before discussing the breakdown of the calculations into phases, some preliminary definitions will be useful. Superscript n on a variable refers to the value of the variable at the beginning of the time step and superscript (n+1) denotes the value at the end. In this discussion a typical cell in the interior of the grid is considered; Section 2.2.2.6 discusses the special conditions which describe the handling of the grid boundaries and the axis of symmetry. For a typical cell, denoted by a value of the index k, the dependent variables for that cell are written $P(k)$, $S_{rr}(k)$, $S_{zz}(k)$, $S_{rz}(k)$, $U(k)$, $V(k)$, $E_m(k)$, $m(k)$, $\rho(k)$, representing respectively the hydrostatic pressure, the three deviator stress terms, the radial and axial components of velocity, the specific internal energy, the mass, and the average density for cell k. The adjacent cells above, below and to the right and left of k are designated respectively as ka, kb, kr, and kl. Here the terms above, below right and left refer to a cross-section view of the cells, in which the left border is parallel to the axis of symmetry with z increasing upward (see Fig. 1). Each cell is, then, the torus obtained by rotating the rectangle (since $\Delta r \neq \Delta z$ in general) about the axis of symmetry. In the discussion that follows, the calculation of the terms on the right of Eqs. (10) through (12) are described sequentially starting with Phase 1.

2.2.2 Phase 1--Effects of Pressures and Deviator Stresses

In Phase 1, the pressure forces and stress deviator forces (if effects of strength are being included) are used to update the velocities and internal energies. The difference equations used in Phase 1 were chosen because they prevent under-dense cells from being "kicked" and therefore, eliminate the need for "GLUEing". An artificial viscosity has also been included in the differencing scheme in order to minimize instability in low velocity stagnation regions.

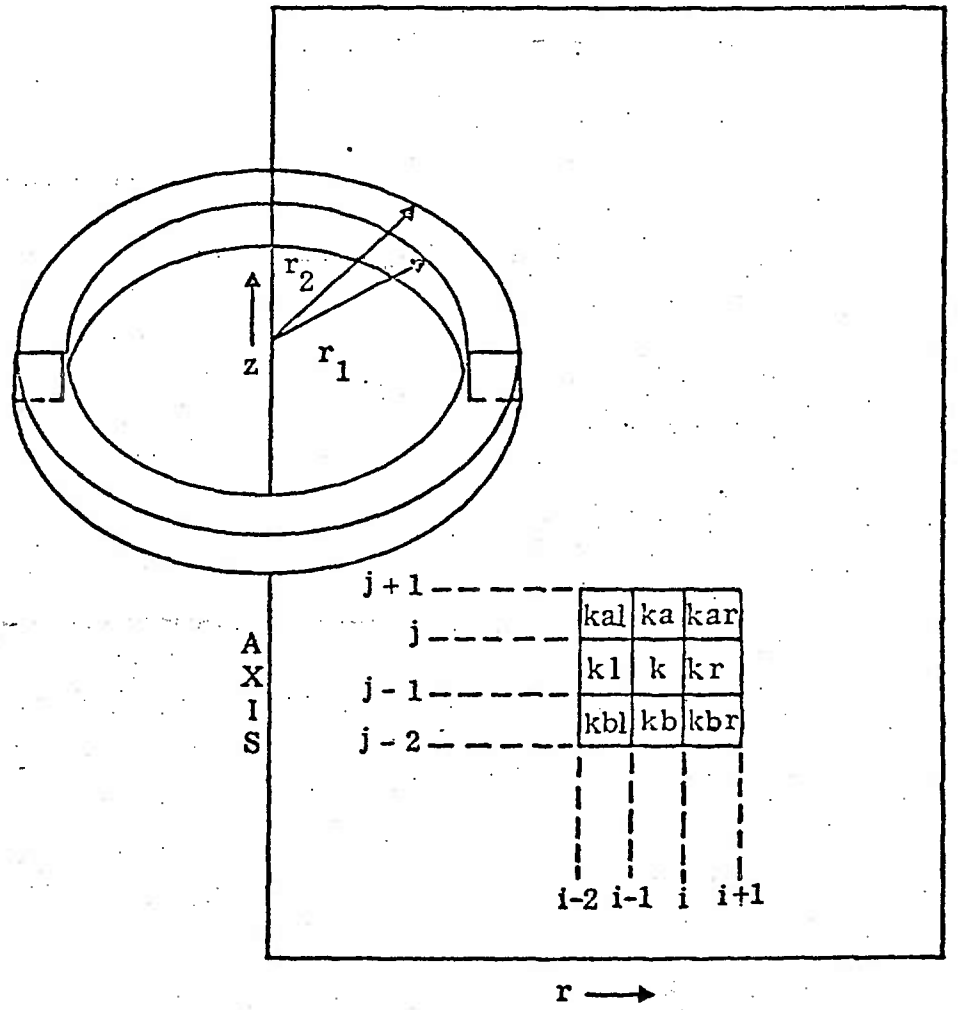


Fig. 1--Grid layout and a typical cell.

The pressures used in Phase 1 are calculated by EQST and set in subroutine CDT. The deviator stresses used are computed in subroutine PH3. If the effects of strength are not being included, the deviator stresses are set to zero.

2.2.2.1 Continuity Equation, (10)

No contribution to Phase 1.

2.2.2.2 Equation of Motion, (11)

1. Axial Motion

The change in axial momentum is:

$$\Delta(mV) = \left[A^b\left(P^b + Q^b - S^b_{zz}\right) - A^t\left(P^t + Q^t - S^t_{zz}\right) + A^r S^r_{rz} - A^\ell S^\ell_{rz}\right] \Delta t$$

2. Radial Motion

The change in radial momentum is:

$$\Delta(mu) = \left[A^\ell\left(P^\ell + Q^\ell - S^\ell_{rr}\right) - A^r\left(P^r + Q^r - S^r_{rr}\right) + A^t S^t_{rz} - A^b S^b_{rz} + \left(A^r - A^\ell\right) \cdot \left(P(k) + S_{rr}(k) + S_{zz}(k)\right)\right] \Delta t$$

2.2.2.3 Energy Equation

The change in total cell energy is:

$$\Delta(mE_T) = \Big\{ A^b\Big[V^b\big(P^b + Q^b - S^b_{zz}\big) - U^b S^b_{rz}\Big] - A^t\Big[V^t\big(P^t + Q^t - S^t_{zz}\big) - U^t S^t_{rz}\Big] + A^\ell\Big[U^\ell\big(P^\ell + Q^\ell - S^\ell_{rr}\big) - V^\ell S^\ell_{rz}\Big] - A^r\Big[U^r\big(P^r + Q^r - S^r_{rr}\big) - V^r S^r_{rz}\Big]\Big\}\Delta t$$

2.2.2.4 Definition of Variables

A^m = area of cell surface m.

P^m = pressure at the interface between cell k and km.

$$p^m = \Big[\rho(k)P(km) + \rho(km)P(k)\Big] / \Big[\rho(k) + \rho(km)\Big]$$

S^m_{rr}, S^m_{zz} = deviator stress at the interface between cell k and km.

$$S^m_{zz} = \Big[\rho(k)S_{zz}(km) + \rho(km)S_{zz}(k)\Big] / \Big[\rho(k) + \rho(km)\Big]$$

S^m_{rz} = shear stress at the interface between cell k and km.

$$S^m_{rz} = \Big[\rho(k)S_{rz}(km) + \rho(km)S_{rz}(k)\Big] / \Big[\rho(k) + \rho(km)\Big]$$

V^m, U^m = axial and radial velocities at the interface between cell k and km.

$$V^m = \left[\rho(k)V(k) + \rho(km)V(km)\right] / \left[\rho(k) + \rho(km)\right]$$

Q^m = pseudo-viscous pressure at the interface between cell k and km.

$$Q^m = C \cdot \left[U(k) - U(km)\right] \sqrt{\left|\left(P^m - S^m_{rr}\right)\left[\rho(k) + \rho(km)\right]/2\right|}$$

in radial direction

$$= C \cdot \left[V(k) - V(km)\right] \sqrt{\left|\left(P^m - S^m_{zz}\right)\left[\rho(k) + \rho(km)\right]/2\right|}$$

in axial direction

and C is a constant = 1 if interface is compressing
= .4 if interface is expanding

2.2.2.5 Extension of Phase 1 to Mixed Cells

If a cell contains more than one material, it is necessary to update the specific internal energies of each material in the cell. This is done by first estimating the sound speed (c_i) in material i. Then

$$\Delta SIE_i = \frac{m(k) \cdot \Delta AIX}{\rho_i^2 c_i^2 \sum_i \frac{m_i}{\rho_i^2 c_i^2}}$$

where ΔAIX is the change in specific internal energy for cell k, m_i is the mass of material i, and ρ_i is the density of material i.

The densities of free surface mixed cells are also updated in Phase 1. This is done by first determining the change in volume for the entire cell as a function of the velocity field according to the formula

$$\Delta VOL = \left[A^{\ell}U^{\ell} - A^{r}U^{r} + A^{b}V^{b} - A^{t}V^{t}\right]\Delta t$$

The density of material i is then updated according to the following expression:

$$\rho_i^{(n+1)} = \frac{1}{\frac{1}{\rho_i^n} + \frac{\Delta VOL \sum m_i/\rho_i^n}{VCELL\ \rho_i^{n^2} c_i^2 \sum \frac{m_i}{\rho_i^{n^2} c_i^2}}}$$

where VCELL = total cell volume. For a cell containing only one material, this reduces to

$$\rho_i^{(n+1)} = \frac{\rho_i^n}{(1 + \Delta VOL/VCELL)}$$

2.2.2.6 Special Considerations Along the Grid Boundaries

It is necessary to define interface values for stresses and velocities at the top, bottom, right and left of the computational grid.

1. Top of Grid (transmittive)

If cell k is at the top edge of the grid,

$P^t = P(k)$ $\qquad$ $S_{rz}^t = S_{rz}(k)$

$S_{zz}^t = S_{zz}(k)$ $\qquad$ $V^t = V(k)$

$U^t = U(k)$ $\qquad$ $Q^t = 0$

and the total theoretical energy is updated by

$$ETH = ETH + A^t\left[V^t\left(P^t - S^t_{zz}\right) - U^t S^t_{rz}\right]\Delta t$$

2. Right of Grid (transmittive)

If cell k is at the right edge of the grid

$$P^r = P(k) \qquad S^r_{rz} = S_{rz}(k)$$

$$S^r_{rr} = S_{rr}(k) \qquad V^r = V(k)$$

$$U^r = U(k) \qquad Q^r = 0$$

and the total theoretical energy is updated by

$$ETH = ETH + A^r\left[U^r\left(P^r - S^r_{rr}\right) - V^r S^r_{rz}\right]\Delta t$$

3. Bottom of Grid (transmittive)

If cell k is at the bottom edge of the grid and the bottom of the grid is transmittive (CVIS < 0)

$$P^b = P(k) \qquad S^b_{rz} = S_{rz}(k)$$

$$S^b_{zz} = S_{zz}(k) \qquad V^b = V(k)$$

$$U^b = U(k) \qquad Q^b = 0$$

and the total theoretical energy is updated by

$$ETH = ETH - A^b\left[V^b\left(P^b - S^b_{zz}\right) - U^b S^b_{rz}\right]\Delta t$$

4. Bottom of Grid (reflective)

If cell k is at the bottom edge of the grid and if the bottom of the grid is reflective (CVIS = 0)

$$P^b = P(k) \qquad S^b_{rz} = 0$$

$$S^b_{zz} = S_{zz}(k) \qquad U^b = U(k)$$

$$V^b = 0 \qquad Q^b = -2 \cdot C \cdot V(k)\sqrt{\left|\left[\rho(k) - S_{zz}(k)\right]\rho(k)\right|}$$

There is no need to update the total theoretical energy for this case since no work is done across a reflective grid boundary.

5. Left Edge of Grid (Axis of Symmetry--reflective)

If cell k is at the left edge of the grid

$$P^\ell = P(k) \qquad S^\ell_{rz} = 0.$$

$$S^\ell_{rr} = S_{rr}(k) \qquad V^\ell = V(k)$$

$$U^\ell = 0. \qquad Q^\ell = -2 \cdot C \cdot U(k)\sqrt{\left|\left[\rho(k) - S_{rr}(k)\right]\rho(k)\right|}$$

There is no need to update the total theoretical energy.

2.2.2.7 Additional Modifications

For the inadequately resolved region in the immediate vicinity of the axis, a change was made to prevent unrealistic positive radial velocities in the jet. Specifically, when the jet material is sufficiently expanded that cell pressures are zero, any remaining positive radial velocity is set to zero and the resulting reduction in kinetic energy is compensated for by increasing the internal energy.

The small radial velocities which are corrected by this procedure are believed to be caused by an artificially overheated jet, the artificial heating being in turn traceable to error in the Phase 2 transport, which is accurate to first order only. It is likely that the correction would not be needed in a very highly resolved calculation.

2.2.3 Phase 2--The Effects of Transport

In Phase 2 the transport of mass, momentum and energy throughout the computational grid is calculated. This transport is determined by integrating the last terms of Eqs. (10) through (12). In the discussion below, primary attention is given to the case of transport between pure cells. At the conclusion of this discussion, the special provisions required to treat mixed cells are described.

2.2.3.1 Continuity Equation

The transport mass is

$$\Delta_2(m) = - \Delta t \int_S \rho u_i n_i ds$$

and is determined for each cell face from

$$\delta m = - \rho^d \bar{u}_i A_i \Delta t \ .$$

ρ^d is the density of the cell from which the mass moves (donor cell), A_i is the area of the face and $\bar{u}_i$ is an interpolated value of the velocity component normal to A_i representing approximately the velocity at the interface at the end of the time step. For example, considering cells k and ka

in Fig. 1,

$$\bar{v} = \frac{\frac{1}{2}\left[v^n(k) + v^n(ka)\right]}{\left[1 + \frac{v^n(ka) - v^n(k)}{\Delta z}\,\Delta t\right]}$$

Calculated transport masses are subtracted from the donor cell mass and added to the acceptor cell mass. This updating is done after the transport terms have been calculated; all transport terms are computed using the pre-transport quantities.

2.2.3.2 Equation of Motion

1. Axial Motion

The term in Eq. (11) for axial momentum transport is

$$\Delta_2\left(mu_j\right) = -\,\delta t \int_s \left(\rho u_j u_i\right) n_i \, ds \ .$$

At each face of the cell the transport specific momentum, u_j, is taken to be the axial velocity of the cell from which the mass moves (donor cell, index kd), i.e.,

$$u_j = v^n(kd) \ .$$

Since the various faces of the cell have different donor cells it is convenient to express the momentum transport for each face

$$\delta(mv) = v^n(kd)\,\delta m$$

where

$$\delta m = -\,\rho^d\,\bar{u}_i A_i \Delta t$$

is the mass which is transported across the cell face, as given in the preceding mass transport calculation. Note that $\delta(mv)$ is the axial momentum and the δm is the mass transported in either the r or z direction, depending on which face of the cell is being computed.

2. Radial Motion

$$\Delta_2(mu_j) = -\Delta t \int_S (\rho u_i u_j) n_i ds$$

and, by analogy with the axial case, the equation for the transport of radial motion across an interface is

$$\delta(mu) = u^n(kd)\ \delta m$$

where $u^n(kd)$ is the time n velocity of the donor cell and $\delta m = -\rho^d \bar{u}_i A_i \Delta t$ is the mass which is transported across the cell face in question, as computed in the continuity equation above.

2.2.3.3 Energy Equation

From Eq. (12) the expression for transport of energy is

$$\Delta_3(mE_T) = -\Delta t \int_S (\rho u_i E_T) n_i ds \ .$$

To evaluate this integral, the transported specific energy is taken to be that of the donor cell, kd, i.e.,

$$E_D = E_m^n(kd) + \frac{1}{2}\left[\left(u^n(kd)\right)^2 + \left(v^n(kd)\right)^2\right]$$

and the total energy transported across a given interface is therefore the product of this specific energy and the associated transported mass computed from the continuity equation, i.e.,

$$\Delta_3\left(E_T\right) = E_D \delta m \ .$$

Once the amount of mass, momentum and energy to be transported is known for all faces of the cell, the cell quantities can be updated to account for these effects. New cell velocities are then determined by dividing the new momenta by the updated cell mass. This fixes the new kinetic energy so that the internal energy can be easily determined since the total energy is known.

2.2.3.4 Extension of Phase 2 to Mixed Cells

The procedure used to treat mixed cells is an extension of the preceding method for transport between pure cells. Specifically, the mass, say for material b, transported across a given interface is, in analogy with the result in Section 2.2.3.1 above, just

$$\Delta_2\left(m_b\right) = \Delta t \int_S \rho_b \, u_i \, n_i \, ds$$

where now ρ_b is the donor cell density for material b and the surface integral is now over just that part of the surface area belonging to material b. The density, ρ_b, is determined by a pressure iteration which is the subject of Section V. The determination of the fractional surface area belonging to a given material is discussed in Section IV, paragraph 4.4.

The momentum transport, in analogy with the pure cell case, is simply the product of the transported mass and the appropriate velocity component (axial or radial) of the donor cell.

The energy transported is the product of the mass transported and the energy per unit mass, kinetic plus internal. The kinetic-energy per gram is the same for all materials in the donor cell since only one cell velocity is computed, but the internal energies are generally different. The internal energies are updated in Phase 1 as described in previous sections.

As in the case of pure cells, final values of cell variables in the mixed cells are easily determined once all the transport quantities have been determined for the cell. The new cell velocity components are calculated by dividing the new momenta by the updated cell mass. This determines the new kinetic energy for each material. The internal energy for each material is that which is necessary to conserve total energy, kinetic plus internal, for the individual materials.

2.2.3.5 Additional Considerations for Free Surface Cells

If a mixed cell is also a free surface cell, an additional flux term is computed for each of the interfaces of the cell. This is an associated volume flux and is determined by dividing the mass flux across each interface by the donor cell density used to compute the mass flux across the interface. Thus, for each interface i, the volume flux for material n is

$$\delta VOL_{n_i} = -\bar{u}_i \, A_{n_i} \, \Delta t$$

where A_{n_i} is the fractional area of material n at interface i. PH2 then updates the density of material n in a free-surface cell by

$$\rho_n^{(n+1)} = \frac{m_n + \sum_i \delta m_{n_i}}{\frac{m_n}{\rho_n^n} + \sum_i \delta VOL_{n_i}}$$

2.3 EQUATIONS OF STATE

There are two equations of state used in BRLSC. The first, used for determining pressures and constant energy compressibilities in the liner, is that due to J. H. Tillotson.[3] Only the condensed form of the equation of state is included since the liner material should not be shocked enough to cause significant vaporization of material. The second equation of state is for the explosive. This is a gamma-law gas equation of state modified to give zero pressures ahead of the detonation front.

2.3.1 Equation of State for the Liner

The subroutine EQST contains the equation of state for the liner and has the form, for $\eta \geq 1 - \frac{A}{2B}$:

$$P = P_c = \left[a + \frac{b}{\frac{I}{I_0 \eta^2} + 1} \right] I\rho + A\mu + B\mu^2 , \qquad (13)$$

and for the constant-energy compressibility

$$\left(\frac{\partial P}{\partial \rho}\right)_I = \left[a + \frac{b\left(\frac{3I}{I_0 \eta^2} + 1\right)}{\left(\frac{I}{I_0 \eta^2} + 1\right)^2} \right] I + \frac{A}{\rho_0} + 2B\mu/\rho_0 \qquad (14)$$

and when $\eta < 1 - \frac{A}{2B}$

$$P = P_c = \left[a + \frac{b}{\frac{I}{I_0 \eta^2} + 1} \right] I\rho - \frac{A^2}{4B} \qquad (15)$$

and

$$\left(\frac{\partial P}{\partial \rho}\right)_I = \left[a + \frac{b\left(\frac{3I}{I_0 \eta^2} + 1\right)}{\left(\frac{I}{I_0 \eta^2} + 1\right)^2} \right] I \qquad (16)$$

In these equations P, I and ρ are pressure, specific internal energy and mass density respectively, $\eta = \rho/\rho_0 = \mu + 1$, and a, b, I_0, A, B, and ρ_0 are constants for the particular material. The values of these constants for ten materials are given in Table 1.

It is necessary to use the preceedings equations for pressure in conjunction with those for compressibility to insure that the pressure increases monotonically with density, i.e., $\left(\partial P/\partial \rho\right)_I > 0$. This is necessary to insure that the pressure iteration scheme for calculating pressures in mixed cells converges.

2.3.2 Equation of State for the Explosive

The pressures and constant energy compressibilities for the explosive are computed in subroutine EOSXPL using a modified gamma-law equation of state.

$$P = P_{ex} = (\gamma-1)\rho \cdot \mathrm{MAX}\left[I_{min}, \left(I - C \cdot I_0\right)\right] \qquad (17)$$

and

$$\left(\frac{\partial P}{\partial \rho}\right)_I = (\gamma-1) \cdot \max\left[I_{min}, \left(I - C \cdot I_0\right)\right] \qquad (18)$$

TABLE 1

EQUATION OF STATE CONSTANTS[†]

Material Code Number	Material	a	b	A dynes/cm²	B dynes/cm²	E_0 ergs/g	ρ_0 g/cm²
1	W	.5	1.04	3.08×12^{12}	2.5×10^{12}	$.222 \times 10^{12}$	19.17
2	Cu	.5	1.5	1.39	1.1	.325	8.9
3	Fe	.5	1.5	1.28	1.05	.095	7.9
4	Al	.5	1.63	.75	.65	.05	2.79
5	Be	.55	.62	1.17	.55	.175	1.8
6	Ti	.5	.60	1.03	.5	.07	4.5
7	Ni	.5	1.33	1.91	1.5	.09	8.9
8	Mo	.5	1.02	2.71	1.65	.045	10.2
9	Th	.4	.86	.53	.5	.025	11.7
10	Pb	.4	2.4	.466	.15	.02	11.3

[†]Dienes, J. K., et al., "An Eulerian Method for Calculating Strength Dependent Deformation," General Atomic Report GAMD-8497, February 1968.

In these equations, P, I and ρ are the pressure, specific internal energy, and mass density respectively, and γ and I_0 are constants for the particular explosive. Values of these constants for eighteen explosives are given in Table 2.

I_{min} is an input parameter (usually about 10^6 ergs) which insures that $\left(\partial P/\partial \rho\right)_I > 0$. The variable C is a flag ranging between 0 and 1 which is used to determine whether a cell is behind (C = 0), intercepted by (0 < C < 1) or ahead (C = 1) of the detonation front (see Fig. 2).

Each cycle, the position of the detonation front is determined by

$$R_d = R_0 + D \cdot T$$

where R_d is the radius of the detonation front, R_0 is the initial radius of detonation, D is the detonation velocity given in Table 2, and T is time. For each cell in the grid, R_{min}, the distance from the center of the detonation to the corner of the cell k closest to the center of the detonation and R_{max}, the distance from the center of detonation to the corner of the cell k furthest from the center of detonation are calculated. Then

$$C = 1 - \max\left\{1, \min\left[0, \left(\frac{R_d - R_{min}}{R_{max} - R_{min}}\right)\right]\right\} \qquad (19)$$

By using this technique and noting that cells containing explosive are originally set up with $I = I_0$ and $\rho = \rho_0$ the pressure in a cell ahead of the detonation front is then $P = (\gamma-1)\rho_0 \cdot I_{min}$. Since there is a pressure cutoff (Pmin) used in the calculation which is computed to be $2(\gamma-1)\rho_0 \cdot$ Imin, the pressure in cells ahead of the detonation are set to zero.

TABLE 2

EQUATION OF STATE CONSTANTS FOR EXPLOSIVES†

Material Code Number	Explosive	D cm/μsec	E_0 ergs/g	ρ_0 g/cm	γ
1	Baratol	.487	1.108×10^{10}	2.610	3.42
2	Comp B, Grade A	.798	5.034	1.717	2.71
3	Comp B-3	.770	5.423	1.715	2.54
4	Cyclotol (77/23)	.825	5.271	1.754	2.73
5	Datb	.752	3.856	1.780	2.89
6	HMX	.911	6.395	1.891	2.74
7	LX-01-0	.684	3.087	1.310	2.93
8	LX-04-1	.847	5.622	1.865	2.72
9	LX-07-0	.864	5.627	1.865	2.76
10	Nitroglycerine	.770	4.519	1.600	2.75
11	Nitromethane	.629	5.238	1.128	2.18
12	Octol (77.6/22.4)	.848	5.134	1.821	2.83
13	PBX-9010	.837	5.283	1.783	2.76
14	PBX-9011	.850	5.453	1.770	2.76
15	PBX-9404-03	.880	6.409	1.840	2.65
16	PETW	.830	4.993	1.770	2.81
17	RDX	.864	5.027	1.767	2.90
18	TNT	.693	3.729	1.630	2.73

†Lee, E. L., H. C. Hornig, and J. W. Kury, "Adiabatic Expansion of High Explosive Detonation Products," Lawrence Radiation Laboratory Report UCRL-50422, May 2, 1962.

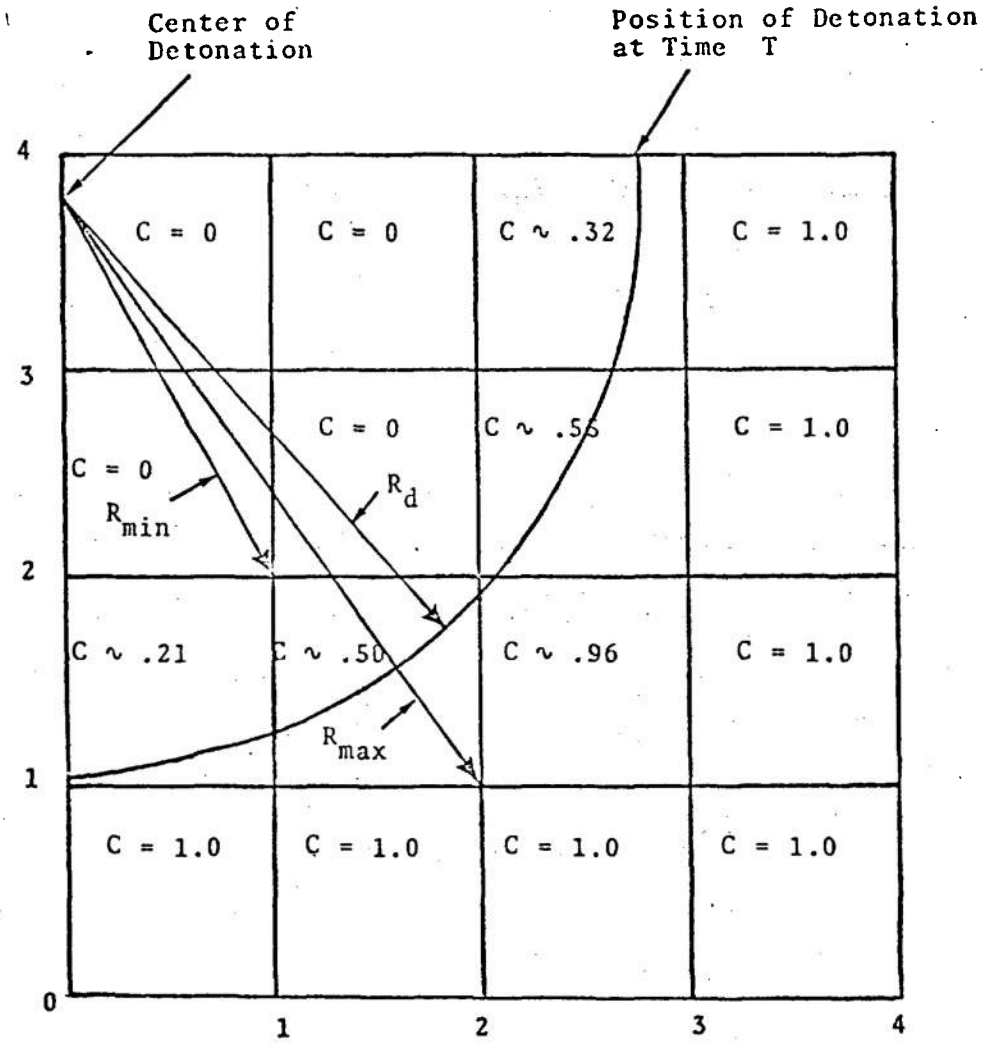


Fig. 2--Calculation of C.

III. NUMERICAL METHOD FOR COMPUTING DEVIATOR STRESSES

3.1 INTRODUCTORY REMARKS

If it is desired to include the effects of material strength in a particular solution, the deviator stresses used in Phase 1 in conjunction with the pressure to update the velocities and internal energies must be recomputed each cycle. This is done in Phase 3 and is explained in the following paragraphs.

3.2 DETERMINATION OF STRAIN RATE DEVIATORS

As a first step in computing stress deviators, the instantaneous strain-rate deviators are computed from the velocity field. In cylindrical coordinates (in rectangular coordinates, the u/x term is zero) these are

$$\dot{\varepsilon}_{zz} = v_y - \frac{1}{3}\left(u_x + v_y + \frac{u}{x}\right)$$

$$\dot{\varepsilon}_{rr} = u_x - \frac{1}{3}\left(u_x + v_y + \frac{u}{x}\right)$$

$$\dot{\varepsilon}_{rz} = \left(u_y + v_x\right)/2$$

Here the cell centered velocity gradients are computed as the difference between interface velocities (a density weighted average velocity) divided by the cell dimension. For example, the interface velocity between cells k and kn is given by

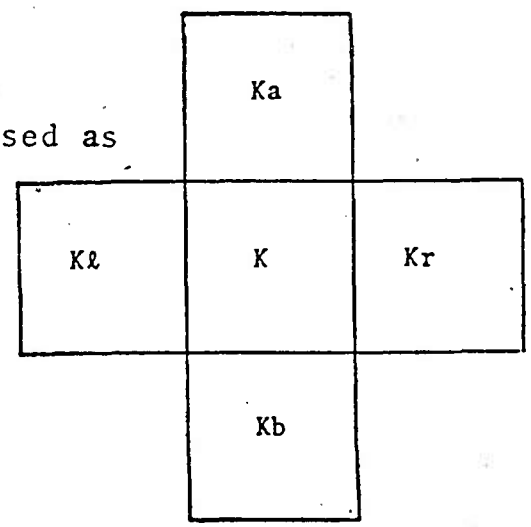
$$v^n = \frac{\rho(k)v(k) + \rho(kn)\ v(kn)}{\rho(k) + \rho(kn)}$$

$$u^n = \frac{\rho(k)u(k) + \rho(kn)\ u(kn)}{\rho(k) + \rho(kn)}$$

and the velocity gradients can be expressed as

$$v_y = \frac{v^a - v^b}{\Delta y} \qquad v_x = \frac{v^r - v^\ell}{\Delta x}$$

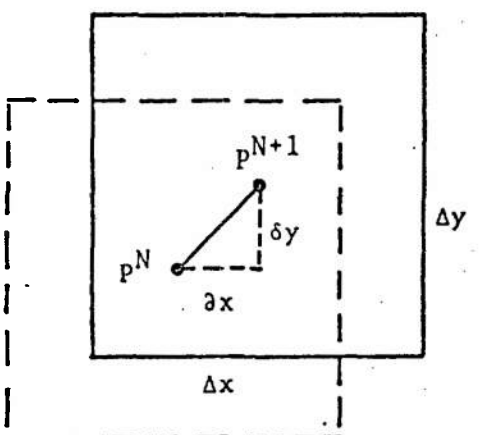
$$u_y = \frac{u^a - u^b}{\Delta y} \qquad u_x = \frac{u^r - u^\ell}{\Delta x}$$



The above calculation provides the strain rate deviator associated with material at the cell center at the beginning of the time step. It is necessary to recognize that constitutive equations are to be applied only along a particle path. To this end, one must take a convective derivative. Consider the time N and position P^N of a particle which, at time $N+1$, will be at the cell center. At time N this point will be offset from the cell center by

$$\delta x = -u(k)\ \Delta t$$

$$\delta y = -v(k)\ \Delta t\ .$$



The strain rate deviators at the offset point P^N are determined by interpolation between cell center strain rate deviators. This is done by weighting the contribution of neighboring cells in proportion to their overlap areas with a rectangle of cell dimensions, centered at P^N. For example, in the above sketch, the weighting factors are

for cell k

$$WK = (\Delta x - |\delta x|)(\Delta y - |\delta y|)$$

for cell in horizontal direction

$$WKH = |\delta x|(\Delta y - |\delta y|)$$

for cell in vertical direction

$$WKV = |\delta y|(\Delta x - |\delta x|)$$

for cell in diagonal direction

$$WKD = |\delta x||\delta y|$$

so that the resulting interpolated value of a strain rate deviator component, say $\dot{\varepsilon}_{rz}$, is given by

$$\dot{\varepsilon}_{rz} = \frac{(WK)\dot{\varepsilon}_{rz}(k) + (WKH)\dot{\varepsilon}_{rz}(kh) + (WKV)\dot{\varepsilon}_{rz}(kv) + (WKD)\dot{\varepsilon}_{rz}(kd)}{WK + WKH + WKV + WKD}$$

Having determined $\dot{\varepsilon}_{zz}$, $\dot{\varepsilon}_{rr}$, $\dot{\varepsilon}_{rz}$ for the mass which will be at the center of cell k at the end of the time step, the deviatoric strain increments can now be calculated.
For ε_{rz}

$$\Delta\varepsilon_{rz} = \dot{\varepsilon}_{rz}\,\Delta t$$

3.3 DETERMINATION OF STRESS DEVIATORS

The deviatoric strain increments are next used in the material constitutive equation, to update the stress deviator tensor s_{ij}. To do this one first needs to compute the stress deviator at time N for the particle in question. This is done by employing the area weighting procedure described above for strain rate deviators.

The deviatoric stress increments, ds_{ij}, are then determined by using the elastic relation

$$ds_{ij} = 2Gd\varepsilon'_{ij}$$

where G is the modulus of rigidity and $d\varepsilon'_{ij}$ are the increments of deviatoric strain. When such an increment of stress causes the yield criterion to be violated each stress component is proportionately reduced to bring the stress state normally back to the yield surface. A variable yield strength

$$Y = \left(K_0 + K_1 P\right)\left(1 - E/E_M\right)$$

is defined, to account for the increase in strength at high pressures and the decrease in strength at elevated temperatures. The three components of deviator stress are updated by

$$s_{zz}^{N+1} = s_{zz}^{N} + 2G\ \Delta\varepsilon_{zz}$$

$$s_{rr}^{N+1} = s_{rr}^{N} + 2G\ \Delta\varepsilon_{rr}$$

$$s_{rz}^{N+1} = s_{rz}^{N} + 2G\ \Delta\varepsilon_{rz}$$

The following yield condition is imposed:

$$s_{ij}s_{ij} = s_{zz}^2 + s_{rr}^2 + s_{\theta\theta}^2 + 2s_{rz}^2 \leq 2Y^2$$

where $s_{\theta\theta} = -\left(s_{rr} + s_{zz}\right)$ and Y is the yield strength in shear. If the above inequality is exceeded during a time step, as would occur in plastic deformation, all of the deviatoric stress components are proportionately reduced. Thus the state of stress has been returned normally to the yield surface. If the second invariant is smaller than $2Y^2$, the stress state is in the elastic regime and the stresses are not reduced.

The preceding calculation updates the s_{ij}, giving values of these quantities at cell centers (as corrected for material convection.) These updated deviator stresses are then used along with the hydrostatic pressures in Phase 1 to recompute the velocities and internal energies.

3.4 MODIFICATIONS FOR GRID BOUNDARIES AND AXIS

The description given above applies to normal cells within the grid. Additional statements must be made to cover grid boundaries and the axis of symmetry.

Grid boundaries may be reflective (bottom grid boundary) or transmittive (bottom, right or top). In calculating the strain rate deviators at reflective grid boundaries (from the velocity field) it is assumed that a row of fictitious cells exists outside the grid. Each cell in this row is assigned the same tangential component of velocity and an equal and opposite normal component of velocity as its real neighbor cell at the grid boundary. Thus, for cell k at a reflective bottom grid boundary, the fictitious cell just below k has velocities

$$u = u(k)$$

$$v = -v(k)$$

These velocities are then used in an otherwise standard (above) calculation of the strain rate deviator tensor for cell k. For transmittive boundary cells, one assumes that the fictitious cell has both of its velocity components equal to the velocity of the cell just inside the boundary.

$$u = u(k)$$

$$v = v(k)$$

With these assumptions, it is then possible to compute strain rate deviators for the border cells.

The axis of symmetry is essentially a reflective grid boundary. In calculating strain rate deviators for the column of cells next to the axis, the cell "to the left" is assumed to have the same axial velocity and an equal and

opposite radial velocity, i.e.,

$$v = v(k)$$

$$u = -u(k).$$

IV. THE PROPAGATION OF TRACER PARTICLES AND THEIR USE TO DESCRIBE MATERIAL INTERFACES

4.1 INTRODUCTORY REMARKS

The most complicated logic of the BRLSC code is found in the subroutines* dealing with the definition and use of material interfaces. Conceptually the task is not difficult. The idea of moving tracer particles with a locally defined velocity and using them to describe the interface between materials is a simple one. Likewise, employing the partial cell boundary areas determined by interface position to compute the mass flux of materials is a very natural use of these interfaces. The complexity of the task comes with making the treatment completely general. As the code is written, there are no restrictions on the direction of the flow, on the shape of the material interface, on the number of times an interface can cross a cell boundary, or on the number of materials contained in a cell.

It is hoped that the present section will aid the user in understanding the organization and logic of these routines. In particular, this section covers the definition of the material interfaces, the computation of fractional cell boundary areas for each material in a mixed cell, and the use of these fractional areas in defining the mass transport terms. The creation of mixed and pure cells, and the propagation of the tracer particles that define the package† boundaries will also be discussed.

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*INFACE, NEWMIX, NEWRHO, FLUX, CALFRC, ADJFLX, MOVTCR

†To distinguish the INFACE and PH2 (Phase 2) functions, it should be noted that the mass transports (for mixed cells) are only computed and stored in INFACE. The actual transport of all quantities, and the associated updating of cell variables, is performed in PH2 for both mixed and pure cells.

4.2 DEFINING MATERIAL INTERFACES

A set of massless tracer particles are initially positioned along the boundary of each material package. These tracers are numbered such that the package is on the left as one proceeds between any two consecutive tracers. The material interface therefore is defined by the line segments connecting these tracers. The initial density of tracers is controlled by input variables.

To prevent the boundaries of adjacent packages from crossing, the tracers along the common boundary coincide exactly. Because these identical points are moved with exactly the same velocity, they remain superimposed during the entire calculation.

Subroutine INFACE is called each cycle to handle these massless tracer particles and to compute the effects that the position of these particles have of mass fluxes, etc. INFACE itself calls a number of subroutines among which are: MOVTCR which moves the tracers with the local velocity field, CALFRC which computes the fractional cell areas defined by the position of the tracers, FLUX which computes the mass flux across mixed cell interfaces and ADJFLX which computes the mass fluxes necessary to transport all the mass out of a cell which has lost an interface.

4.3 ADVANCING TRACER PARTICLES

The first thing that INFACE does each subcycle* is to call MOVTCR to move the tracer particles.

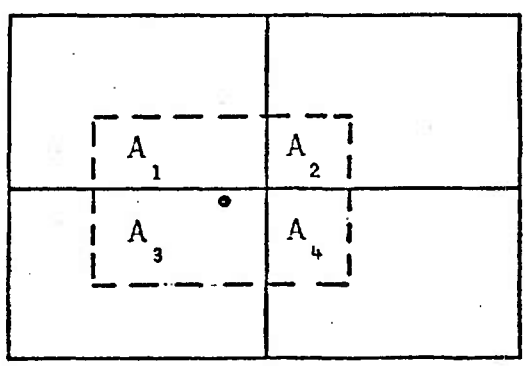
Each material is circumscribed by a series of massless tracer particles, which are propagated each time step a distance†

$$\Delta x_i = \vec{u}_i \cdot \Delta t$$

where $\vec{u}_i$ is a local average velocity vector for the continuum, determined by an area overlap method which gives weight to velocities in the surrounding cells. Specifically, a rectangle of cell dimensions is superimposed on the particle to be moved and then

$$\vec{u}_i = \frac{\sum_L \vec{w}(L)\, A_L \rho(L)}{\sum_L A_L \rho(L)}$$

$$L = 1, \ldots, 4$$



*Subroutine INFACE is subcycled to minimize transport noise.

†Since the tracer coordinates are in grid line units, this distance is converted from centimeters to cell units.

where $\rho(L)$ is the density and $\vec{w}(L)$ is the cell-centered velocity* of the overlapped cell L and A_L is the overlap area. This procedure gives a spatially continuous velocity field for particle propagation.

The passive, cell-centered tracers (XP, YP), used only for plotting the mass flow within the package boundaries, are moved by the same method.

4.3.1 Additional Modification to Insure Realistic Jet Definition

An additional consideration must be made, when moving the interface tracers, to insure that the jet is well defined. Since the tracers are moved with an area weighted velocity and since a very large velocity gradient exists near the stagnation point at early times, some of the tracers describing the inside surface of the liner near the axis aren't moved downward fast enough. This error arises when the overlap area extends into the relatively low velocity region near the stagnation point and causes a very uneven interface to form. An example of this can be seen in Fig. 3. To overcome this problem, a special modification has been included in the tracer moving subroutine (MOVTCR) of BRLSC. This is outlined below:

1. When the problem is first set up, a function describing the position of the tracers along the inside surface of the liner is derived, ($y = f(x)$, x, y in cm) and the free surface tracers which are defined by this function identified. i.e., the tracers TX(NVOID,NS), TY(NVOID, NS) through TX(NVOID,ND), TY(NVOID,ND) define the inside surface of the tracer.

*These cell-centered velocities have been updated by PH1 (pressure and strength effects) for this time step.

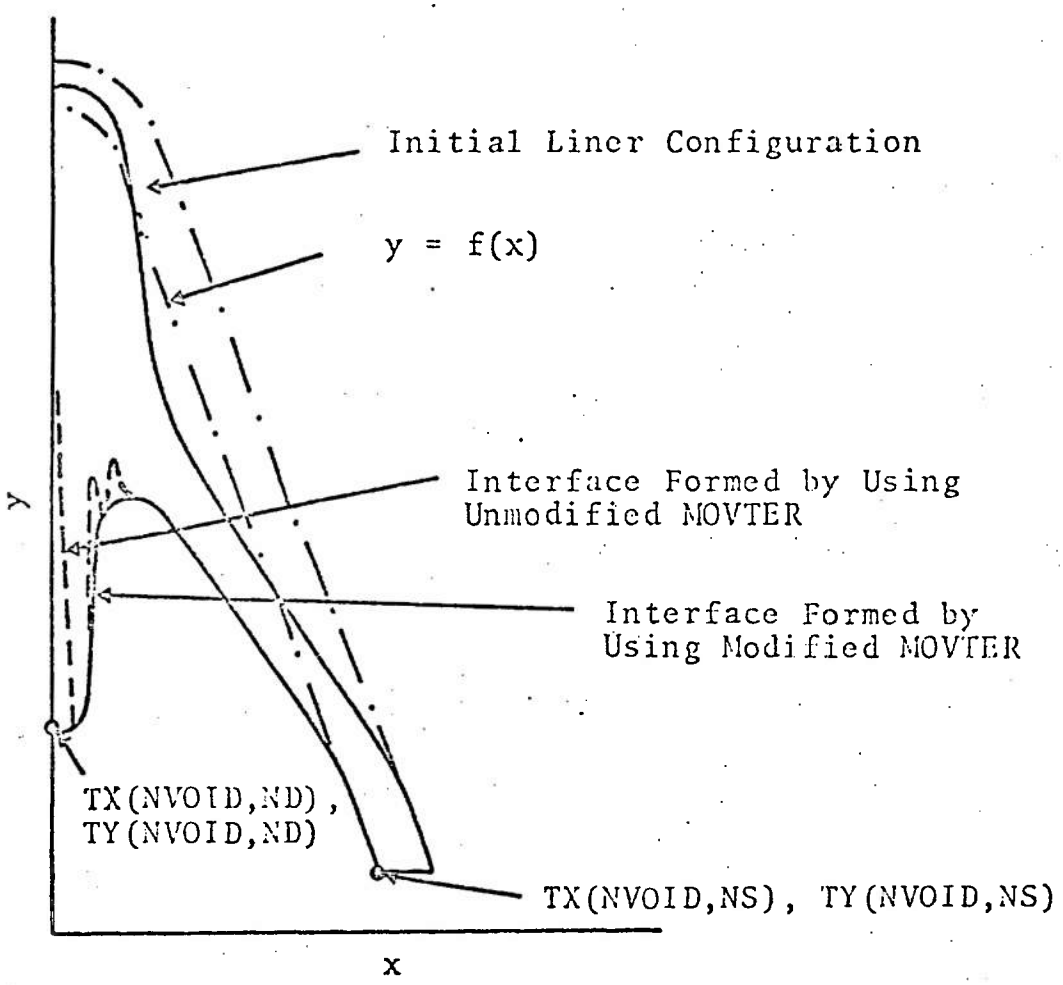


Fig. 3--Comparison between modified and unmodified versions of subroutine MOVTER

2. In MOVTCR, the physical coordinates (cm) for each tracer are computed. Thus, when moving the free surface tracers, x_N, y_N is the physical location of tracer TX(NVOID,N), TY(NVOID,N).

3. The tracers are then moved so that tracer N moves from $\left(x_N^n, y_N^n\right)$ to $\left(x_N^{n+1}, y_N^{n+1}\right)$.

4. y_N^{n+1} for free surface tracers in the range $ND \geq N > NS$ (defined in Step 1) are then repositioned

$$y_N^{n+1} = MIN\left[y_N^{n+1},\ y_{N-1}^{n+1} + f\left(x_N^{n+1}\right) - f\left(x_{N-1}^{n+1}\right)\right]$$

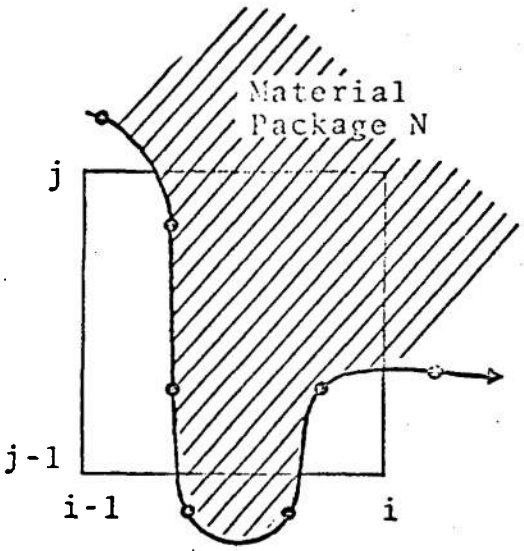
5. The new physical coordinates for the tracers are then converted back to cell coordinates.

6. The coordinates of the tracers for material package 1 (the liner) are set equal to the appropriate free surface tracers moved with the above method.

4.4 COMPUTING FRACTIONAL AREAS

4.4.1 Problem Definition

When an Eulerian cell is cut by the material N interface, we are interested in knowing what fraction of each side of the cell should be associated with material N.



For example, the fractional areas associated with material N in the diagram above are as follows:

$$\text{Left} = 0$$

$$\text{Top} \sim .8\pi \left(x_i^2 - x_{i-1}^2\right)$$

$$\text{Right} \sim .7\left(y_j - y_{j-1}\right) 2\pi\, x_i$$

$$\text{Bottom} \sim .3\pi\left(x_i^2 - x_{i-1}^2\right)$$

These fractional areas are used in computing the mass flux of material N across each side of the mixed cell. (Actually, for each mixed cell it is necessary to compute and store only the fractional areas for the right and top sides since the cells below and on the left provide the information for the

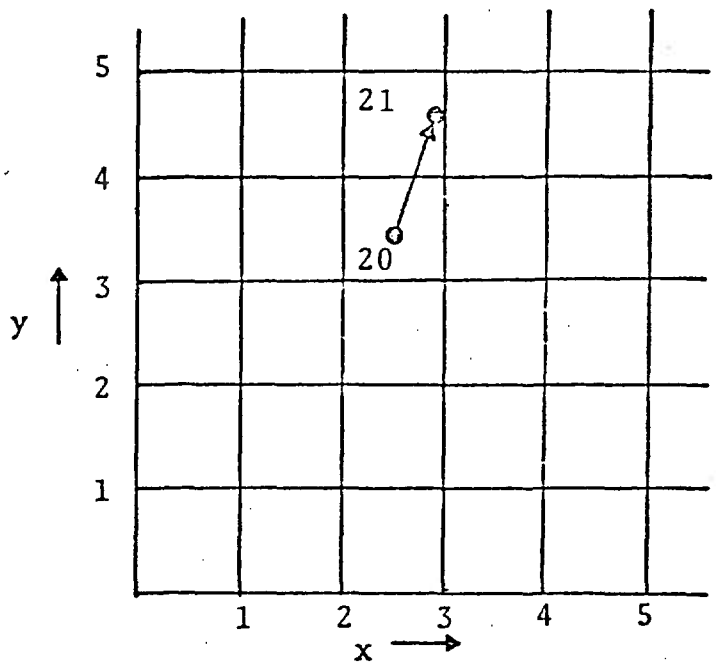
other two sides.) The method given below for computing these fractional areas puts no restrictions on how many interfaces are in a cell or on how many times a single interface crosses a cell boundary. It does, however, assume that a material package boundary never crosses itself, and experience has shown that when it does the logic of INFACE breaks down. This is not a limitation of the method since the boundary will not cross itself while running a shaped charge problem.

4.4.2 Computing Intersections of Interfaces with Grid Lines

During each subcycle through INFACE, subroutine CALFRC is called to compute fractional cell areas for mixed cells.

Subroutine CALFRC considers consecutively (two at a time) the tracer points which circumscribe each material package in a counter-clockwise direction. For simplicity, the coordinates of the tracers are in grid line units rather than centimeter units. Thus the coordinates of a pair of tracers immediately indicate whether they straddle one or more cell boundaries.

TX and TY are the FORTRAN variable names of a tracer's x and y coordinates, respectively. The arrays are doubly dimensioned; the first dimension identifies the material package, the second gives the sequential ordering of the points. In the example shown below, the indices indicate that both tracer points belong to material package one (first index) and that they are consecutive points (second index), namely the 20th and 21st points describing package one. The x-coordinates indicate the line through the points does not intersect a vertical grid line, whereas the y-coordinates indicate the line through the points intersects the fourth horizontal grid line.



TX(1,20) = 2.5
TY(1,20) = 3.5

TX(1,21) = 2.8
TY(1,21) = 4.6

4.4.3 Defining Fractional Areas of Intersected Cell Boundaries

Subroutine CALFRC defines the point of intersection of the line between two tracers and a grid line and uses it to define the fractional area of the particular cell boundary associated with material package one. The code recognizes from the sequential numbering of the points that material one is on the left of the point of intersection.

The FORTRAN variables FRACTP and FRACRT store the fractional areas of the top and right boundaries, respectively, for all the materials of a mixed cell. These arrays are also doubly dimensioned and are written as FRACTP(N,M) and FRACRT(N,M) where the first dimension, N, identifies the material package number and the second dimension, M, is an index that links the mixed cell K to the special mixed cell arrays by the relation, M=FLAG(K)-100. (See Appendix C.)

If material package two is adjacent to material package one, the material two tracers are identical to the material one tracers, but are numbered in opposite order. For example, package two tracers (say 30 and 31) that coincide with the package one tracers discussed previously would be as follows:

TX(2,30) = 2.8

TY(2,30) = 4.6

TY(2,31) = 2.5

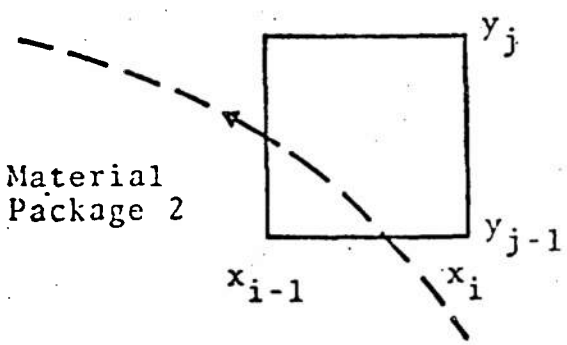
TY(2,31) = 3.5

The fractional area to the right of the intersection point is associated with material package two, and is stored in FRACRT (2,M).

4.4.4 Defining Fractional Areas of Boundaries Not Intersected

Because the fractional area is a term in the flux equations applied to mixed cells, it must be defined for the right and top boundary of every mixed cell even if one or both are not intersected by a material interface. In that case the fractional area either equals the total cell boundary area or is zero, e.g.

Material Package 1



$$FRACTP(1,M) = \pi\left(x_i^2 - x_{i-1}^2\right)$$

$$FRACRT(1,M) = \left(y_j - y_{j-1}\right)2\pi\, x_i$$

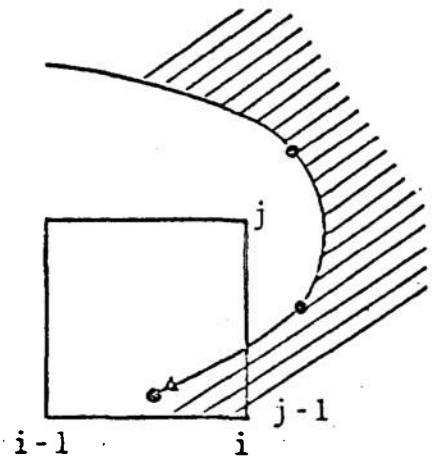
FRACTP(2,M) = 0.

FRACRT(2,M) = 0.

In the above example, none of the material of package two is transported across the right or top boundaries of the cell. On the other hand, the full cell area is used to compute the mass flux of the material of package one across these boundaries. There is clearly a need to systematically define the fractional areas of mixed cell boundaries that are not intersected by a material interface. The following discussion illustrates how the fractional area of these non-intersected boundaries are correctly defined by "presetting" them when the interface enters a cell and "resetting" them when it leaves.

The direction of an interface, given by the sequential order of the tracer points, determines whether one is entering a cell or leaving it. When entering a cell, and if crossing this cell boundary for the first time, the program processes the other sides of the cell in a clockwise order and presents their fractional areas to equal the total cell boundary area until it comes to a side that has already been crossed by the same material interface (i.e., a side which has an associated fractional area that is non-zero and is less than the total area.)

Case (1)



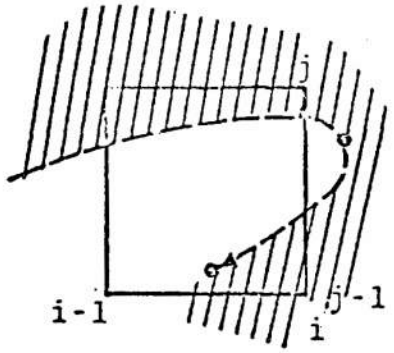
Fractional areas preset:

$$\text{Bottom} = \pi\left(x_i^2 - x_{i-1}^2\right)$$

$$\text{Left} = \left(y_j - y_{j-1}\right)2\pi\, x_{i-1}$$

$$\text{Top} = \pi\left(x_i^2 - x_{i-1}^2\right)$$

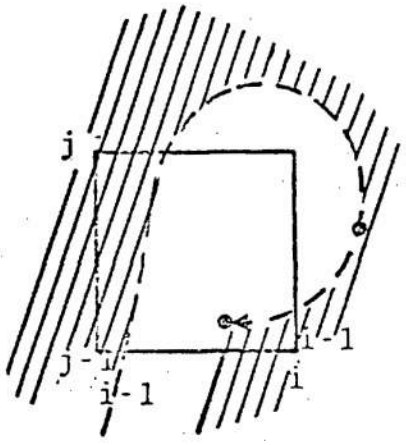
Case (2)



Fractional areas preset:

Bottom = $\pi\left(x_i^2 - x_{i-1}^2\right)$

Case (3)



Fractional areas preset:

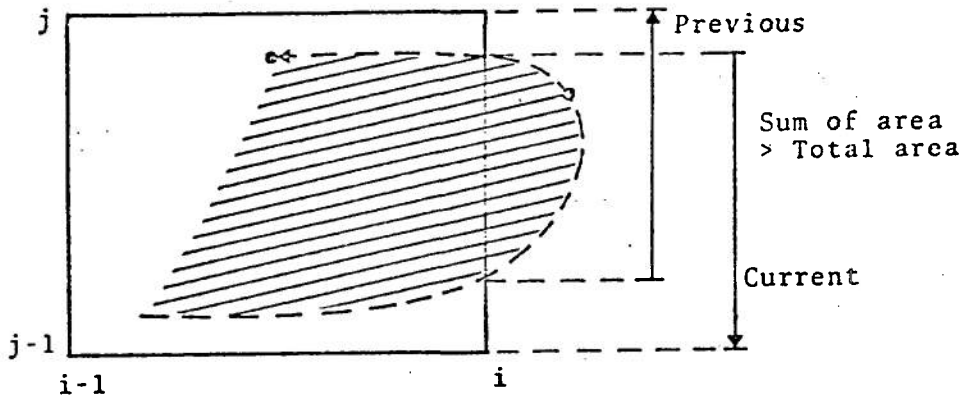
None

If the interface of material N crosses a cell boundary for the second time, the code does not preset the fractional areas when material N is between the two points of intersection (Case 4). If material N is outside the two points, the fractional areas are preset as described above (Case 5). The program senses that material N is between the points when the sum of the fractional area computed on the previous crossing(s) and the one computed currently is greater than the total area.

Case (4)

Fractional areas preset:

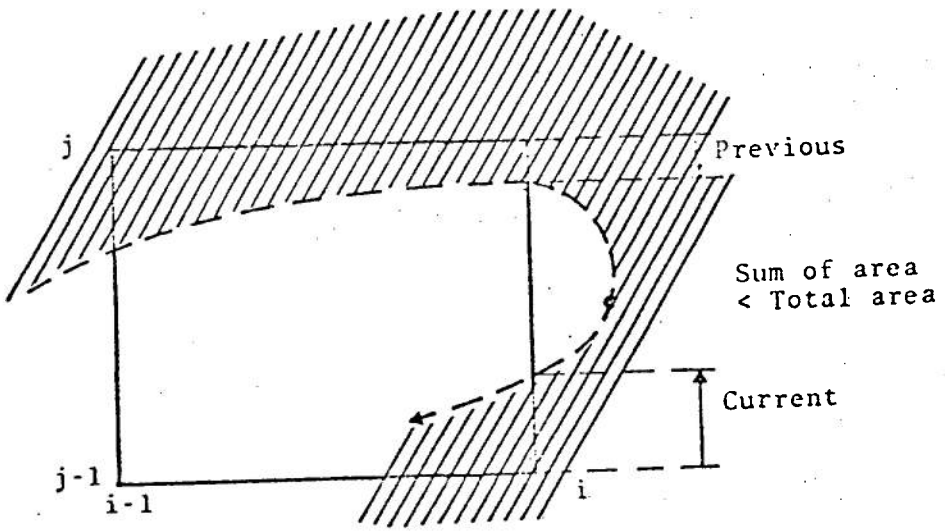
None



Case (5)

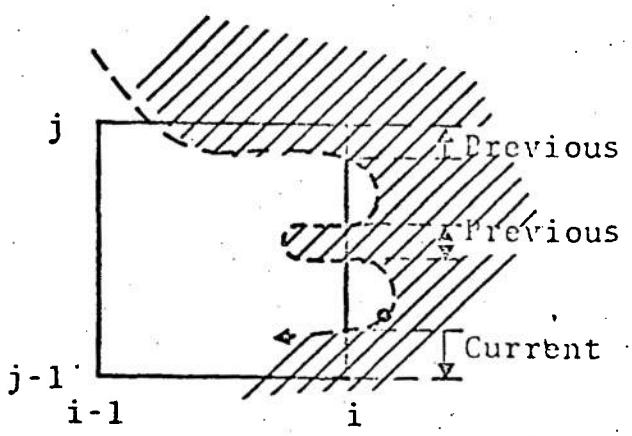
Fractional areas preset:

Bottom = $\pi\left(x_i^2 - x_{i-1}^2\right)$



Actually this rule holds regardless of how many times the interface crosses the boundary, as illustrated by Case 6 and Case 7.

Case (6)



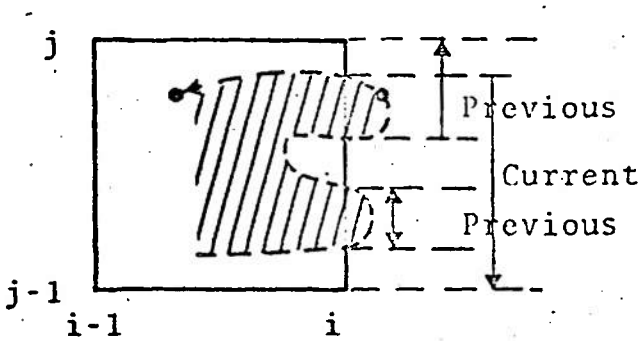
Fractional areas preset:

$$\text{Bottom} = \pi\left(x_i^2 - x_{i-1}^2\right)$$

$$\text{Left} = \left(y_j - y_{j-1}\right)2\pi\, x_{i-1}$$

Sum of areas
< Total area

Case (7)



Fractional areas preset:

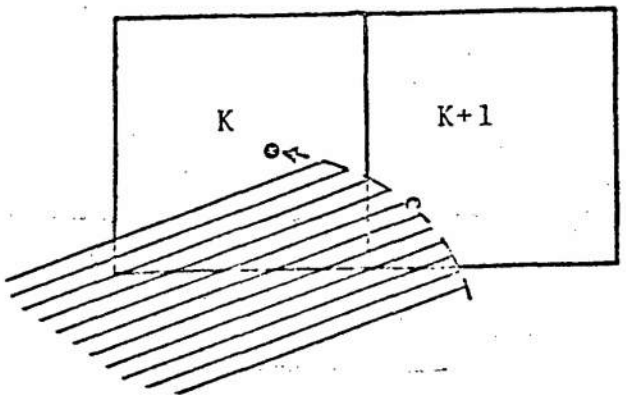
None

Sum of areas
> Total area

When the interface enters cell K from the right, it has just left cell K+1, and the program must "reset" to zero the fractional areas of certain non-intersected sides of cell K+1.

In Cases 8 through 10 the side where the interface leaves is crossed only once by this interface. Proceeding in a clockwise direction from the side the interface has left, the program resets to zero the fractional areas of the non-intersected sides until it encounters a side that is intersected by this interface.

Case (8)

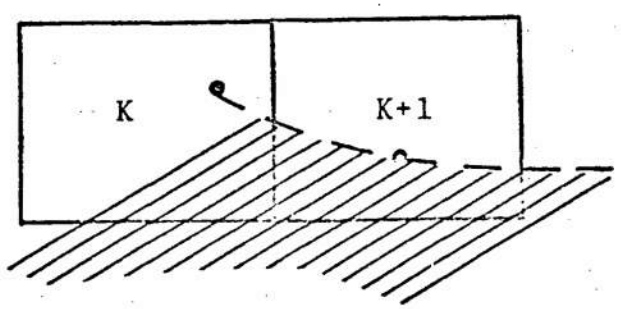


Fractional areas reset:

Top = 0.

Right = 0.

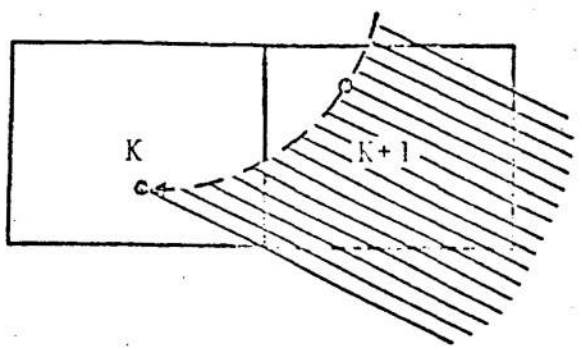
Case (9)



Fractional areas reset:

Top = 0.

Case (10)

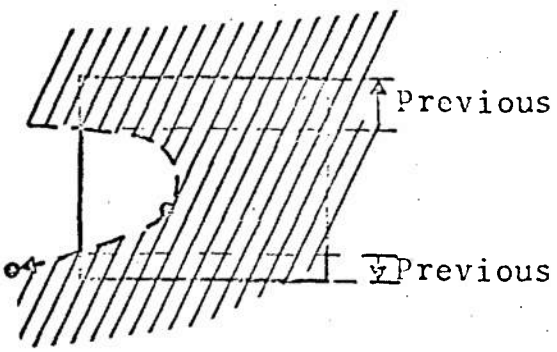


Fractional areas reset:

None

In Cases 11 and 12 below, the side where the interface leaves has been previously crossed by this interface. The program sums the fractional areas resulting from a previous crossing of that boundary and the current crossing. If the sum of these areas is less than the total cell boundary area (Case 11) none of the fractional areas of the other sides are reset. If the sum is greater (Case 12), the program proceds to reset to zero the areas of the other non-intersected sides of the cell.

Case (11)

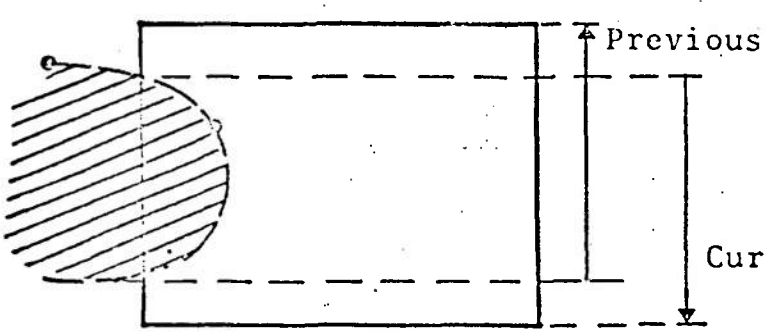


Fractional areas reset:

None

Sum of areas
< Total area

Case (12)



Fractional areas reset:

Top = 0.

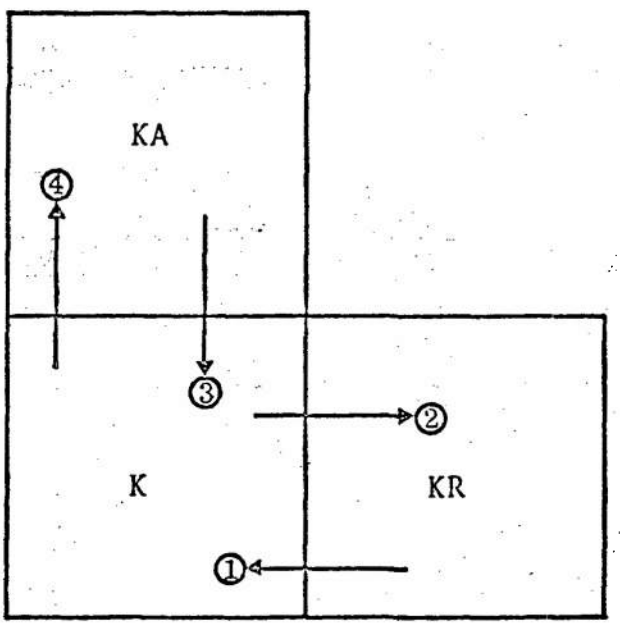
Right = 0.

Bottom = 0.

Sum of areas
> Total area

The calculation of the fractional areas is thus reduced to considering four directions of an interface with respect to a specified cell K:

1. entering cell K, leaving cell KR
2. entering cell KR, leaving cell K
3. entering cell K, leaving cell KA
4. entering cell KA, leaving cell K.



4.5 COMPUTING THE FLUX TERMS FOR INTERFACE CELLS

The computation of fractional cell boundary areas is performed in order to use the material interface positions to define the mass flux of materials across interface cell boundaries. For pure cells the mass flux (computed in Phase 2) between two cells is

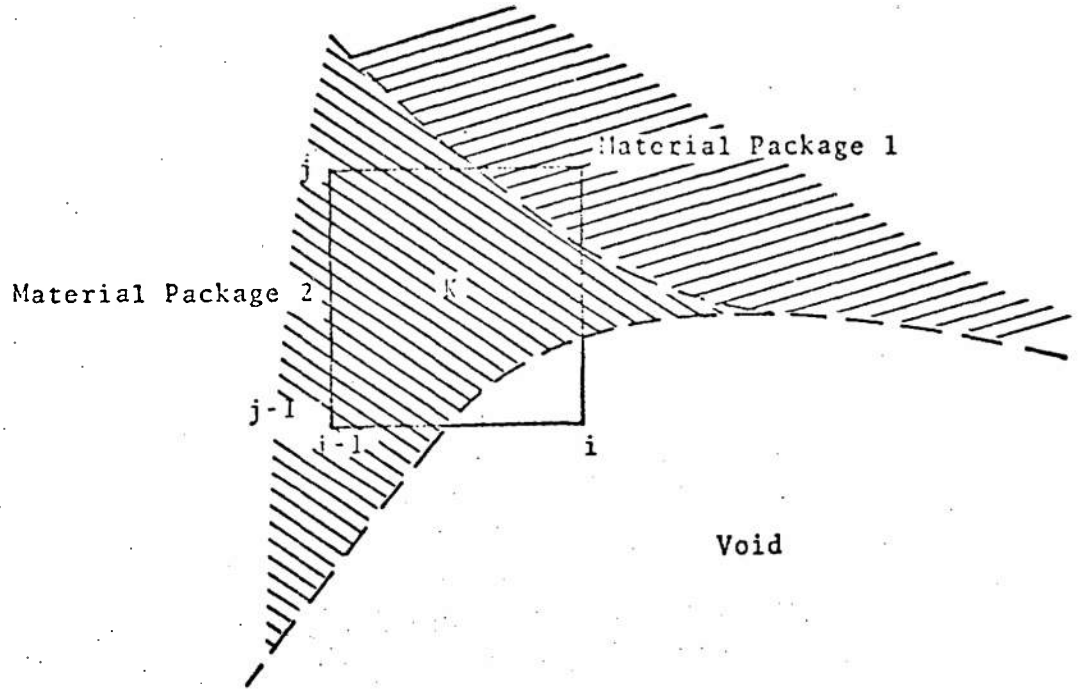
$$\Delta m = \rho_T \, V_T \, A \, \Delta t$$

where ρ_T is the donor cell density, V_T is an average of the cell-centered velocities of the two cells, and A is the area of the cell boundary for which the mass flux is being computed.

For cells crossed by an interface this equation becomes

$$\Delta m_N = \rho_{TN} \, V_T \, FA_N \, \Delta t/S$$

where ρ_{TN} is the donor material N density, FA_N is a fractional cell boundary area for material N, and the time step, Δt, is divided by S, the number times the INFACE subroutine is subcycled. Thus an interface cell has mass flux terms (which are calculated in subroutine FLUX) for its right and top boundaries associated with each material package in the grid.



In the case shown above, assume there are two material packages in the grid. There are four mass flux terms associated with cell K. Using the FORTRAN variables and assuming M is the location in the mixed cell arrays associated with cell K, the right boundary fluxes would be

$$|\text{SAMMP}(1,M)| \sim \rho_{T1}\, U_T\, .292\left(y_j - y_{j-1}\right)2\pi\, x_i\, \Delta t/s$$

$$|\text{SAMMP}(2,M)| \sim \rho_{T2}\, U_T\, .375\left(y_j - y_{j-1}\right)2\pi\, x_i\, \Delta t/s$$

and the top boundary fluxes would be

$$|\text{SAMPY}(1,M)| \sim \rho_{T1}\, V_T\, .417\left(x_i^2 - x_{i-1}^2\right)\pi\, \Delta t/s$$

$$|\text{SAMPY}(2,M)| \sim \rho_{T2}\, V_T\, .583\left(x_i^2 - x_{i-1}^2\right)\pi\, \Delta t/s$$

The sign of these fluxes indicates the direction of the flow.

4.6 CREATING MIXED CELLS

4.6.1 Assigning Storate Location

Initially those cells containing a material interface are created in SETUP when the problem is generated. Later, as the interfaces move across the grid, new mixed cells are created in NEWMIX (called by CALFRC which is called by INFACE). Whenever a cell boundary is straddled by a pair of consecutive tracers, INFACE checks that both cells (K and K´) on either side of the boundary are mixed. If one or both are pure (i.e., MFLAG(K) < 100, or MFLAG(K´) < 100), subroutine NEWMIX is called and an unused* storage location in the mixed cell arrays is assigned to that cell. [The maximum number of mixed cells at any one time is controlled by the input variable NMXCLS which should correspond to the dimensions of the mixed cell arrays. If the user tries to generate more than NMXCLS mixed cells, NEWMIX calls for an error exit.) Before a cell K becomes mixed, its flag, MFLAG(K), indicates what material package it belongs to. NEWMIX uses that information, transferred through a variable MO in blank common, to define the mixed cell variables for the newly mixed cell, as illustrated by the following FORTRAN statements.

```
MO = MFLAG(K) (when pure)
(M = storage location for cell K in mixed cell arrays)
MFLAG(K) = M+100                          (flag)
XMASS(MO,M) = AMX(K)                      (mass)
SIE(MO,M) = AIX(K)                        (specific internal energy)
RHO(MO,M) = AMX(K)/[TAU(I)*DY(J)]         (density)
```

*A storage location M is not in use if RHO(1,M) = -1.

A cell that becomes "mixed" in INFACE has only one material until subroutine PH2 is executed and the other materials are transported into it. Note also that PH2 will not transport material of another package into a pure cell. The interface of the other package must first cross the cell's boundary in INFACE before the cell can receive the material of the other package in PH2.

4.6.2 Defining Free Surface Cells

A cell containing a free surface often contains only one material and yet is still treated as a mixed cell since an interface crosses its boundaries and the fluxes across its boundaries are a function of the fractional areas computed in INFACE by CALFRC. Of course, it is possible for a cell containing a void (i.e., a free surface) to contain more than one material. A "free surface" cell K is flagged by setting RHO(NVOID,M) = 1., where NVOID is one more than the number of material packages in the problem and M = MFLAG(K)-100.

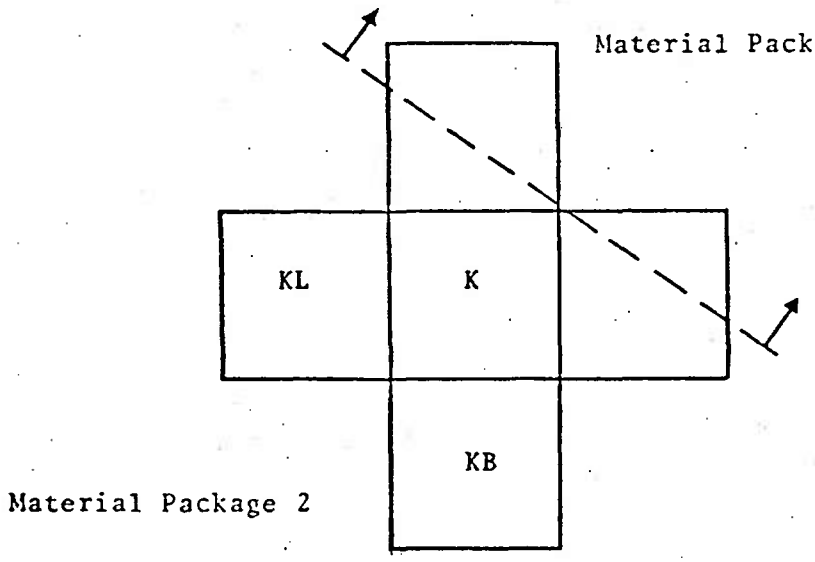
4.6.3 Accounting for Subcycles

INFACE usually is subcycled, i.e., the routine is executed several times each cycle using a fraction of the time step on each subcycle. It is therefore possible to create a mixed cell after one or more subcycles of INFACE have been completed. In that case the flux terms (SAMMP, SAMPY) for that cell have not been accumulated for the completed subcycles and need to be computed before adding in the flux terms for the current and subsequent subcycles. Therefore, when INFACE has completed at least one subcycle, NEWMIX calls FLUX after setting up the storage for the new mixed cell.

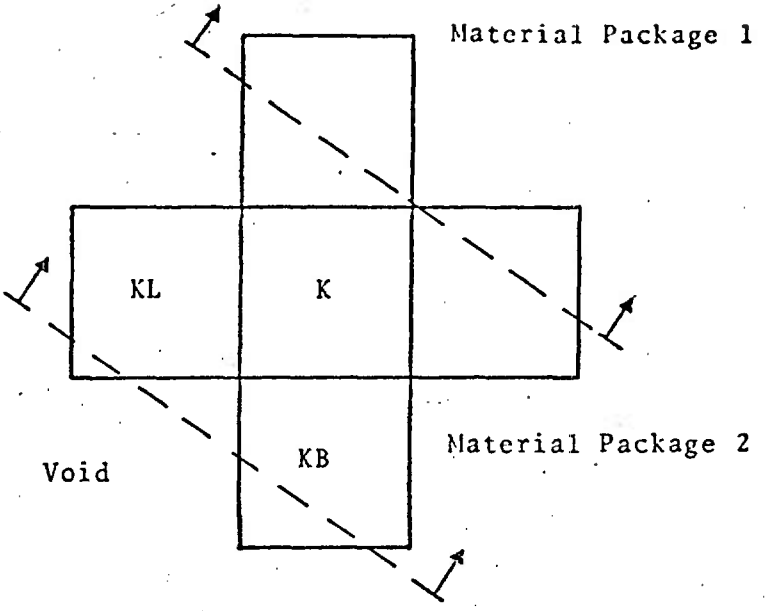
4.7 CREATING PURE CELLS

4.7.1 Defining Material that Remains in the Cell

After the fractional areas associated with each material package have been computed, INFACE searches for cells that were interface cells on the previous cycle but no longer are cut by an interface. Such a cell has become pure and its flag, MFLAG, is made negative to signify that fact until the transport has been completed in PH2. To determine what material package a new pure cell K belongs to, INFACE first looks for a neighbor that is pure and assumes cell K will belong to the same package as one of its pure neighbors, e.g., in the following diagram,



the cell below is pure (MFLAG(KB) = 2), therefore cell K has become a pure cell belonging to package 2. In case all four neighbors are mixed, the cells KB and KL are examined as illustrated in the following example.



Since cell K is not crossed by an interface it follows that if the fractional area of the top of cell KB for package 2 is the total cell boundary area then cell K must belong to package 2. The cell on the left of cell K is used analogously if cell K is in the bottom row of the grid.

4.7.2 Evacuating Materials

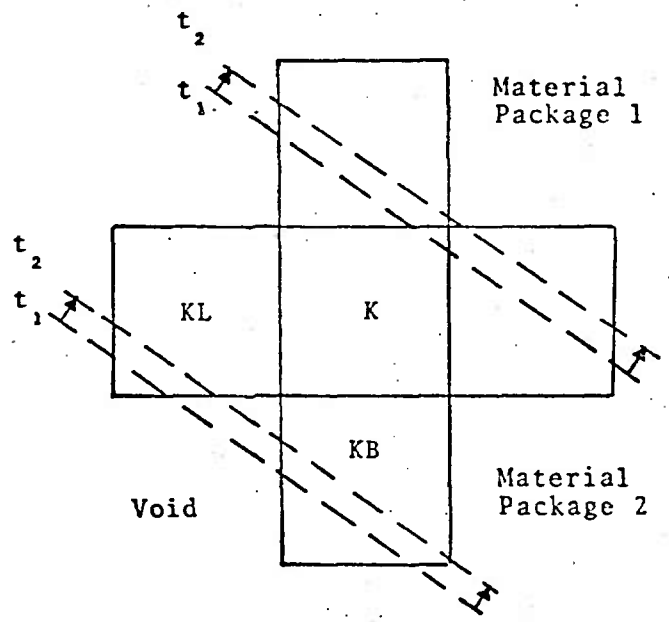
To signify that a material interface has passed out of cell K, the density of that material is set to zero. For example, consider the figure above assuming there are two material packages in the grid; the densities of cell K are redefined until the end of the cycle as follows:

$$M = MFLAG(K) - 100$$

$$RHO(1,M) = 0.$$

$$RHO(2,M) \neq 0.$$

These zero densities are later used as a signal to adjust the fluxes of material 1 so that the material will be exactly evacuated from cell K. This adjustment of the fluxes usually occurs twice in INFACE by calling subroutine ADJFLX, once during the first subcycle (for cells that become pure during the first subcycle) and once after all subcycles are completed (for cells that become pure after the first subcycle). For the first case the flux terms for mixed cells (SAMMP, SAMPY) are saved from the previous cycles to indicate the direction of the flow and the direction of the evaluation. In the following example, t_1 represents time, and ML and MB are locations associated with the mixed cells on the left of and below cell K, respectively:



t_1 flux terms

SAMMP(1,M) > 0.

SAMPY(1,M) > 0.

SAMMP(1,ML) = 0.

SAMPY(1,MB) = 0.

At t_2, the t_1 flux terms indicate that any mass of package 1 still in cell K should be evaluated out the right and top boundaries, not the left or bottom. These evacuation procedures are used for a cell that has lost one interface but is still cut by another interface (so is still mixed) as well as for cells that have become pure.

V. THE PRESSURE AND DENSITY ITERATION FOR MIXED CELLS

5.1 GENERAL METHOD

For ordinary one-material cells, it is possible to compute the pressure directly from the material density and specific internal energy. For cells containing more than one material, it is necessary to make additional assumptions in order to determine cell pressure. In the present method, the cell pressure for mixed cells is determined by an interation procedure. Specifically, the densities of the various materials within the cell are varied, subject to the restriction that the cell be exactly filled by the masses therein, until the individual pressures converge to a common value, taken to be the cell pressure. This process gives, in addition to the cell pressure, the densities of the individual materials for subsequent use in the Phase 1 energy partition and in the Phase 2 transport calculation.

The procedure for determining the pressure and the densities in a mixed cell is actually divided into two parts, a pre-iteration calculation to assure that the cell is filled exactly and an iteration calculation to converge on the desired P's and ρ's.

5.2 PRE-ITERATION CALCULATION

In general, the masses and densities which exist at the beginning of the calculation do not exactly fill the cell since cell masses were changed in the Phase 2 calculation of the previous cycle. The pre-iteration calculation fills the cell exactly by taking account of the constant-energy compressibilities of each of the various materials. Stepwise, this is done by:

1. Calling EQST to compute P_i and C_i^2 $\left[=\left(\partial P_i / \partial \rho_i \right)_{E_i}\right]$ from the old values of ρ_i and E_i (assumed constant throughout the calculation) for each material in the cell.

2. Normalizing (see proof below) the densities to fill the cell exactly

$$\Delta V_i = -\Delta P / h_i^2$$

where

$$h_i^2 = \rho_i^2 C_i^2 = \rho_i^2 \left(\frac{\partial P_i}{\partial \rho_i}\right)_{E_i} ,$$

$$\Delta P = \frac{(VOL - VCELL)}{\sum \frac{m_i}{h_i^2}}$$

$$VOL = \sum \frac{m_i}{\rho_i} ,$$

and

$$m_i = \text{mass of constituent } i$$

and

$$\text{VCELL} = \text{volume of the cell.}$$

The above increments in specific volume are used to obtain the new specific volumes according to

$$V_i = V_{iold} + \Delta V_i$$

and

$$\rho_i = 1/V_i$$

then gives the desired new densities, causing the cell to be filled exactly. This can be shown as follows:

$$m_i V_i = m_i \left(V_{iold} + \Delta V_i \right)$$

$$= m_i/\rho_{iold} - m_i \Delta P/h_i^2$$

$$= m_i/\rho_{iold} - \frac{m_i (\text{VOL-VCELL})}{h_i^2 \sum_j \frac{m_j}{h_j^2}}$$

Summing over all constituent materials gives

$$\sum_i m_i V_i = \text{VOL} - (\text{VOL-VCELL}) \frac{\sum_i \frac{m_i}{h_i^2}}{\sum_j \frac{m_j}{h_j^2}} = \text{VCELL}$$

and shows that the new volumes $m_i V_i$ of the constituents add up to the total cell volume.

5.3 ITERATION CALCULATION

Given that $p_i = f_i(V_i, E_i)$ and $C_i^2 = (\partial P_i/\partial \rho_i)_{E_i}$ (calculated by EQST) for materials $i = 1, \ldots M$, it is desired to find cell pressure, $\bar{P}$, by varying the V_i $(= 1/\rho_i)$ until the P_i's are equal within some specified accuracy, subject to the restriction that the cell remains exactly filled and that the E_i are held constant.

The equation of volume conservation is

$$\sum m_i \, \Delta V_i = 0$$

and the equation that causes material i to undergo a change in specific volume V_i, such that its pressure changes from its current value $P_i^N = f_i(V_i, E_i)$ to a value $\bar{P}^{N+1}$, common to all materials in the cell at the end of the iteration cycle, is

$$\Delta V_i = \left(\bar{P}^{N+1} - P_i^N\right)\left(\frac{\partial V_i}{\partial P_i}\right)_{E_i} \qquad i = 1, \ldots M$$

where

$$\left(\frac{\partial V_i}{\partial P_i}\right)_{E_i} = \frac{-1}{\rho_i^2\left(\frac{\partial P_i}{\partial \rho_i}\right)_{E_i}} = \frac{-1}{\rho_i^2 \, C_i^2}$$

These equations, for $i = 1, 2, \ldots, M$ can be regarded as $M+1$ equations for $M+1$ unknown quantities, ΔV_i and $\bar{P}^{N+1}$. Other quantities in the equations are either known constants (m_i) or are updated each cycle of the iteration $\left[P_i^n \text{ and } (\partial V_i/\partial P_i)_{E_i}\right]$ and are taken to be constants while

solving these equations for ΔV_i and $\bar{P}^{N+1}$. The solutions are

$$\bar{P}^{N+1} = \frac{\sum P_i^n \, W_i^N}{\sum W_i^n}$$

and

$$\Delta V_i = \frac{1}{h_i} \left(P_i^N - \bar{P}^{N+1} \right)$$

where

$$h_i = \left(\frac{\partial P_i}{\partial V_i} \right)_{E_i} = - \rho_i^2 \left(\frac{\partial P_i}{\partial \rho_i} \right)_{E_i} = - \rho_i^2 \, C_i^2$$

and

$$W_i = m_i / h_i \, .$$

That these equations are solutions to the given equations can be verified by direct substitution.

The iteration would be exact (single cycle convergence) if the input coefficients $\left(\partial P_i / \partial V_i \right)_{E_i}$ were constants, since the solution does not involve additional approximations. However, since this is not the case, the coefficients and the pressures are necessarily recomputed each step of the iteration by calling subroutine EQST with the V_i generated during the previous step.

Stepwise, the iteraction calculation is as follows:

1. Call EQST to find $P_i = f_i(V_i, E_i)$ and $\left(\partial V_i / \partial P_i \right)_{E_i}$

2. Compute new $\bar{P}^{N+1}$

3. Compute new ΔV_i from above formulas.

4. Update V_i^{N+1} by adding the above ΔV_i to the old specific volume.

5. Return to (1) using the new values for V_i.

The iteration is complete when the P_i's all equal $\bar{P}$ to some preset accuracy. Usually, convergence is obtained in a maximum of two or three steps if the convergence criterion $|P_i - \bar{P}| < 10^{-3} \bar{P}$ is used.

VI. THE PRESSURE BOUNDARY CONDITION

The BRLSC code has the option of applying a time and position dependent pressure boundary condition.

6.1 GENERAL METHOD

When a pressure boundary condition is to be applied, subroutine APLYPR is called at the beginning of CDT. This subroutine identifies the section of the moving surface along which the pressure force is to be applied and determines which cells are cut by that portion of surface. Those cells are flagged and the coordinates of a point in the cell which lies on the surface are determined. These coordinates, along with the time, are used as input to subroutine PRESBC* which determines the pressure, density and internal energy of the driving material at that position and time. The pressure, density and internal energy are then returned to APLYPR which iterates on the density of the material already in the cell until the pressure of that material is equal to the pressure which was returned from PRESBC. From the mass and new density of the material in the cell, the volume which the material occupies is determined and the volume of the void remaining in the cell computed. The volume of the void is then filled with mass with the density and internal energy which was returned from PRESBC. The total cell mass and internal energy and the total theoretical energy in the problem are updated to reflect this extra mass and energy and the cell pressure is set equal to the desired driving pressure. When all cells cut by the pressure-loaded section of the free surface have been flagged, the pressures set and the masses and energies updated, APLYPR returns to CDT.

*The user must supply subroutine PRESBC if a pressure boundary condition is to be employed.

Any cells which have had their pressures set in APLYPR are ignored during the pressure iteration section of CDT but are included when determining the time step.

After the pressures have been defined along the desired section of the material boundary, they are used to accelerate the material. This is done in PH1 by calling subroutine FAKMAT for all cells which have been flagged by APLYPR. FAKMAT looks at the four cells which surround the cell being processed. If a neighboring cell is flagged as being a void cell, the interface between that cell and the cell (K) being processed by PH1 is considered to be a transmittive boundary. The interface pressure (which PH1 had set equal to zero) is reset equal to the pressure of cell K and the work done at the interface is added to the total theoretical energy of the problem. PH1 then utilizes the new values for interface pressures to update the cell's velocity and internal energy. The energy is then partitioned between the original material in the cell and the artificially added driving material which was added by APLYPR.

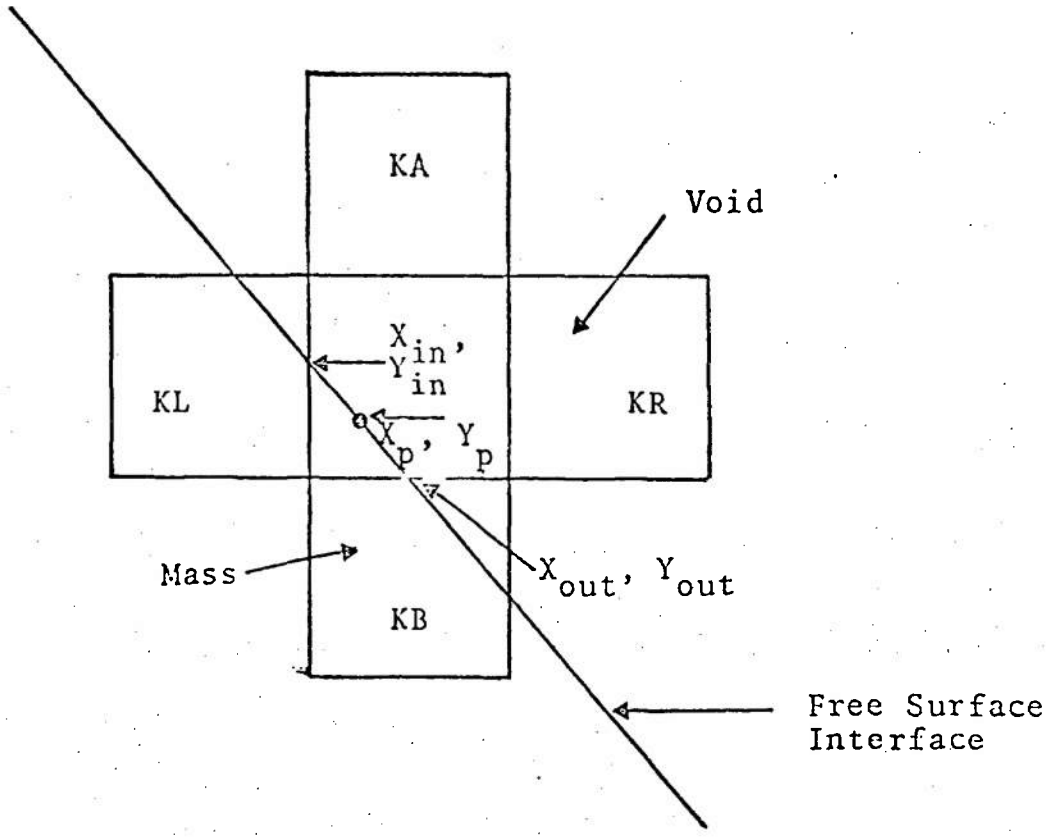
The last step in applying the pressure boundary condition is to call RMVMAT at the end of PH1. This subroutine removes the mass and energy of the material which was added by APLYPR, redefines the total cell mass and internal energy, and updates the total theoretical energy to reflect the reduction in total energy. The flags that were set by APLYPR are unset and RMVMAT returns control to PH1. At this point, the grid again contains only one material but its total energy and momentum reflect the work and impulse delivered it by the pressure boundary conditions.

Subroutine RMVMAT is also called from one other place in the code. Since restart tape dumps are made in EDIT, and EDIT is called after CDT and before PH1, the cell masses and

internal energies written on the tape include the artifically added mass and energy added by APLYPR. It is therefore necessary to call RMVMAT after INPUT and before CDT any time a problem is being restarted in order to restore the grid to the pre-CDT condition it had before the tape dump was made.

The following section shows step by step how the pressure boundary condition is applied.

6.2 STEP-BY-STEP APPLICATION OF THE PRESSURE BOUNDARY CONDITION



6.2.1 Subroutine APLYPR

Subroutine APLYPR, called at the beginning of CDT, follows the interface tracers which define the portion of the material boundary along which the pressure force is to be applied and determines which cells it intercepts (in the above sketch, the interface enters cell K at (X_{in}, Y_{in}) and leaves at (X_{out}, Y_{out}). Then, for each cell K:

(1) Compute $X_p = \frac{1}{2} (X_{in} + X_{out})$

$Y_p = \frac{1}{2} (Y_{in} + Y_{out})$.

(2) Call PRESBC to find:

$P_X = f_p(X_p, Y_p, T)$

$\rho_X = f_\rho(X_p, Y_p, T)$

$E_X = f_e(X_p, Y_p, T)$

(3) Iterate on ρ_ℓ (the density of liner material in cell K) until

$P_\ell = f(\rho_\ell, E_\ell) = P_X$

where E_ℓ = specific internal energy of the liner material and P_ℓ is the pressure.

(4) Use the updated value for ρ_ℓ to compute the volume of K which will be filled with explosive

$Vol_X = VCELL - m_\ell/\rho_\ell$

(5) Fill the cell with mass (with values defined by PRESBC) and update the total theoretical energy to reflect this added mass and energy

$\Delta m = \rho_X \cdot Vol_X$

$ETH = ETH + \Delta M\left(E_X + \frac{1}{2} (U(K)^2 + V(K)^2)\right)$

$AIX(K) = (AMX(K) \cdot AIX(K) + \Delta m \cdot E_X)/\left(AMX(K) + \Delta m\right)$

$AMX(K) = AMX(K) + \Delta m$

(6) Define pressure in cell

$$P(K) = P_X$$

6.2.2 Pressure Calculations in CDT

When control returns from APLYPR to CDT, the pressures in all cells along which the pressure force is to be applied have been defined. Also, the masses, and energies in these cells have been updated to simulate the existence of the explosive material in the cells. CDT skips these cells when computing cell pressures since their pressures have already been computed.

6.2.3 Special Treatment for Pressure Loaded Cells in PH1

(1) Special consideration must be given to any cell interface which exists between a cell which has had its pressure defined by APLYPR and a void cell. It must be remembered that if the driving material were actually in the problem instead of being defined by a function (PRESBC), cells bordering the interface cells that have had their pressures set would not be void but would contain the driving material. It then becomes necessary to treat these special cell interfaces as being interfaces between two cells containing material instead of as an interface between a cell containing material and a void cell. This is done by subroutine FAKMAT which identifies these special cell interfaces and sets their values of velocities and pressures so that these cells can be treated as if they were transmittive boundaries. Referring to the previous sketch, consider the interface between cell K and void cell KR. During the normal execution of Phase 1, the following interface values would be computed as (see Section 2.2.2):

$$P^r = 0.$$

$$U^r = U(K)$$

$$V^r = V(K)$$

$$S^r_{rr} = 0.$$

$$S^r_{rz} = 0.$$

Then, before the velocities and energies in cell K are updated in PHI, subroutine FAKMAT would be called. FAKMAT would redefine the interface pressure:

$$P^r = P(K)$$

and update the total theoretical energy in the problem by

$$ETH = ETH + A^r \cdot U^r \cdot P^r \cdot \Delta t \ .$$

The interface value of pressure between cell K and void cell KA would also be modified in a similar manner.

(2) Once the total change in internal energy for the entire cell has been computed (ΔAIX) it is necessary to increment the internal energy in the liner (ΔSIE_ℓ). This is done by applying the following equation

$$\Delta SIE_\ell = \frac{AMX(K) \cdot \Delta AIX}{\rho_\ell^2 \, C_\ell^2 \left\{ \frac{M_\ell}{\rho_\ell^2 C_\ell^2} + \frac{(AMX(K) - M_\ell)}{\rho_X \gamma_X \rho(K)} \right\}}$$

where ρ_X and γ_X were determined in PRESBC and C_ℓ is the sound speed in the liner.

(3) After the applied pressure force has been used to update the velocities and energies in the interface cells, the mass and associated energy which was added by APLYPR must be removed. This is done by calling RMVMAT at the end

of PH1. RMVMAT redefines the total theoretical energy,

$$ETH = ETH + M_{\ell} E_{\ell} - AMX(k) \cdot AIX(k) + \frac{1}{2}\left[M_{\ell} - AMX(k)\right]\left[U(K)^2 + V(K)^2\right]$$

and redefines the total cell mass and energy

$$AMX(K) = M_{\ell}$$

$$AIX(k) = E_{\ell}$$

At the end of PH1, the momentum and energy of the liner material has been updated to reflect the impulse and work delivered to it by the applied pressure boundary condition.

VII. SAMPLE CALCULATIONS

In this section of the report, selected results from three calculations are given. The three calculations were chosen to demonstrate the three modes in which problems can be run with BRLSC (see Section 8.3.1.1). For a more detailed description of several problems run by BRLSC, see Ref. [7].

7.1 THE BRL PRECISION SHAPED CHARGE

This problem* was run in mode 1 using the Shaped Charge reported in Ref. [4]. The explosive was octol and the liner was copper with a thickness of .081 inches and a half angle of 21 degrees. The liner was set up in an Eulerian grid with square cells (DX = DY = .145 cm). Strength effects were not included in the calculation since earlier calculations had shown that including strength in shaped charge calculations has a negligible effect on the resulting jet.

Figures 4 and 5 show the configurations at various times. For further details about this problem, see Ref. [7].

7.2 AN ARTIFICIALLY DRIVEN SHAPED CHARGE LINER

This problem** was run to demonstrate the results obtained by running a problem in mode 2 (using a time and position dependent pressure force along the outer surface of the liner). The liner, a shortened version of the 105 mm shaped charge liner[5], was copper, .106 inches thick, and had a half angle of 21 degrees. The grid contained square

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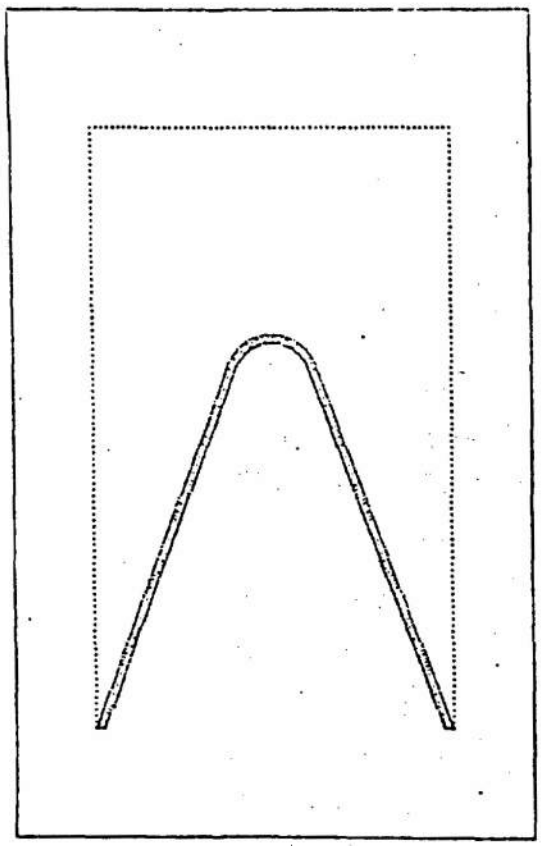
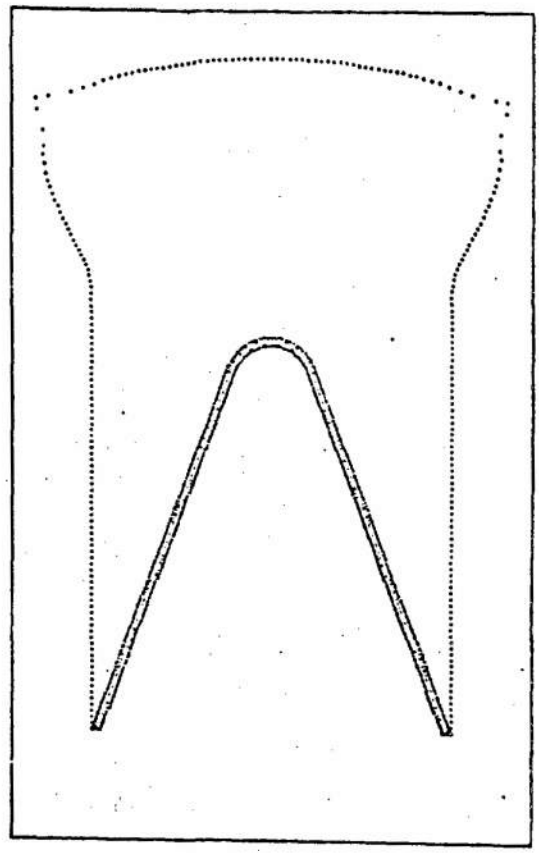
* This problem had 3600 cells in the Eulerian grid and took 102 minutes to run 471 cycles (55.0 μsec) on a Univac 1108.

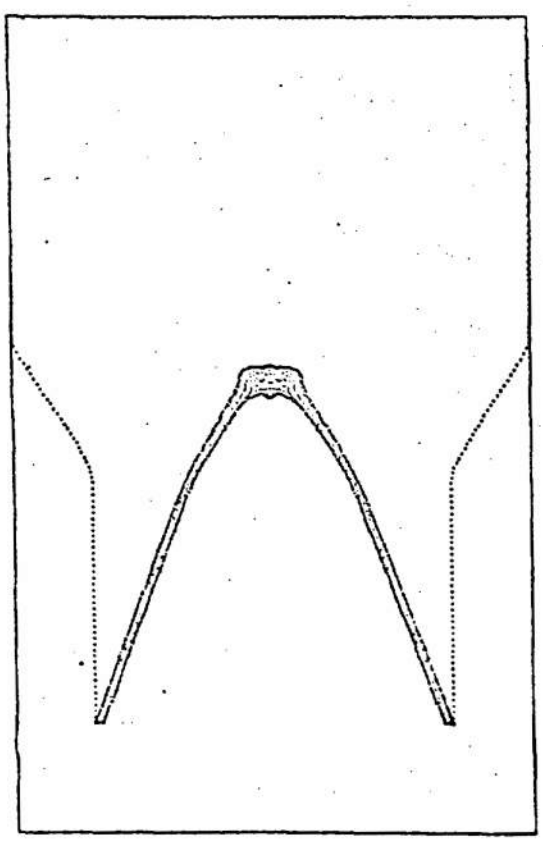
** This problem had 2100 cells in the Eulerian grid and took 10.5 minutes to run 196 cycles (10.0 μsec) on a CDC 6600.



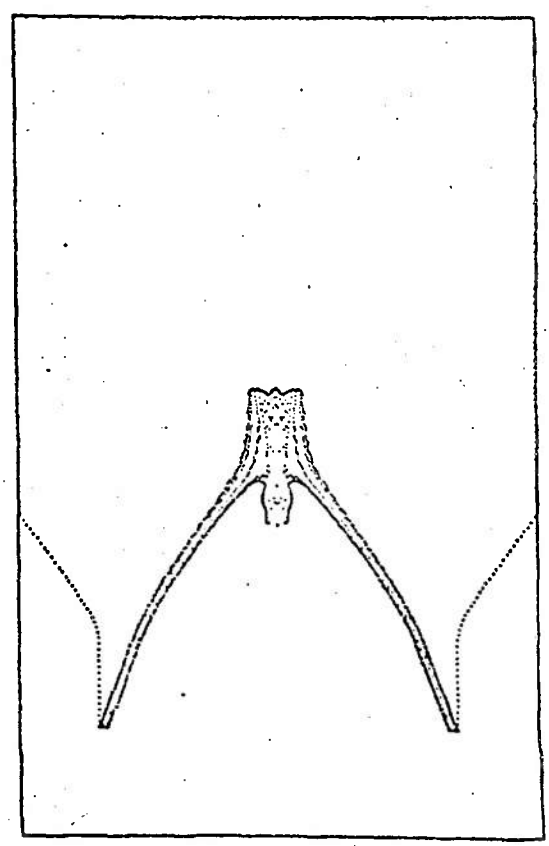
t = 0.0



t = 5.0 μsec

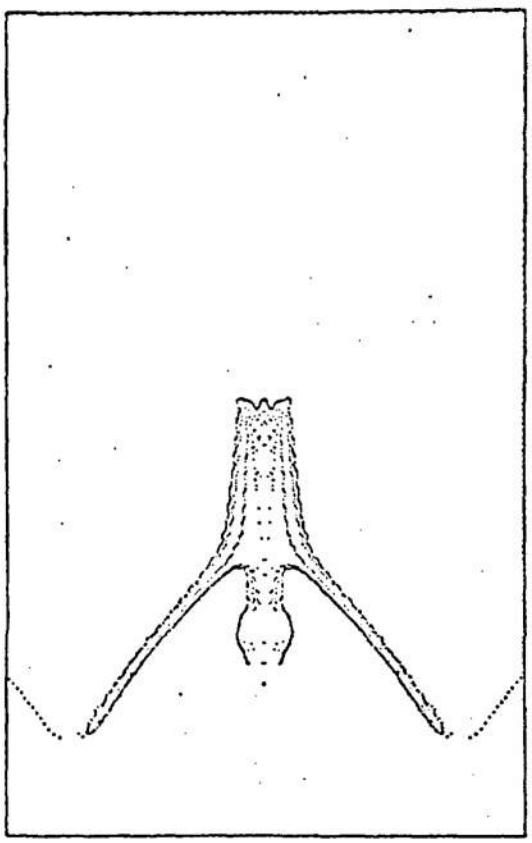


t = 10.0 μsec

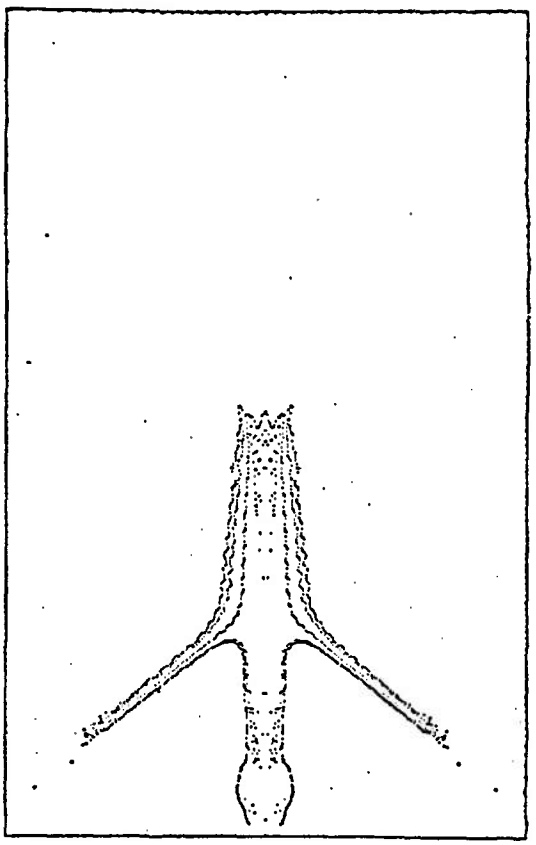


t = 14.0 μsec

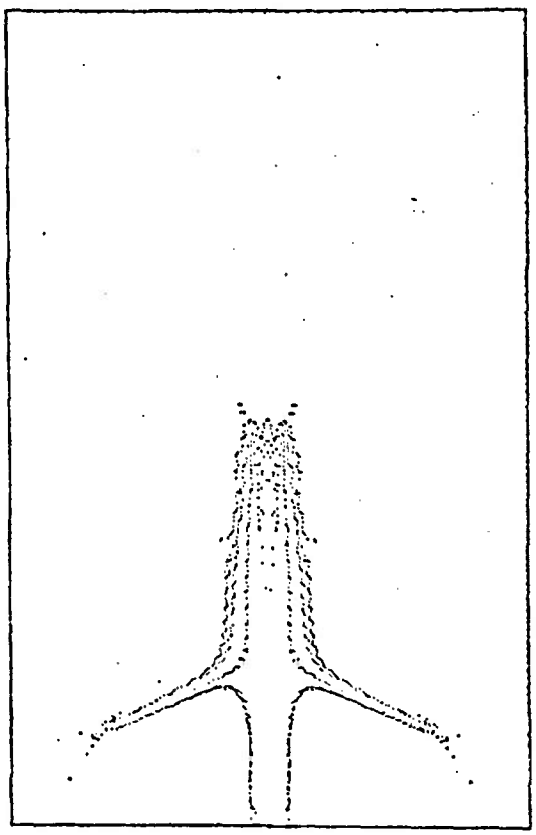
Fig. 4--BRL precision shaped charge.



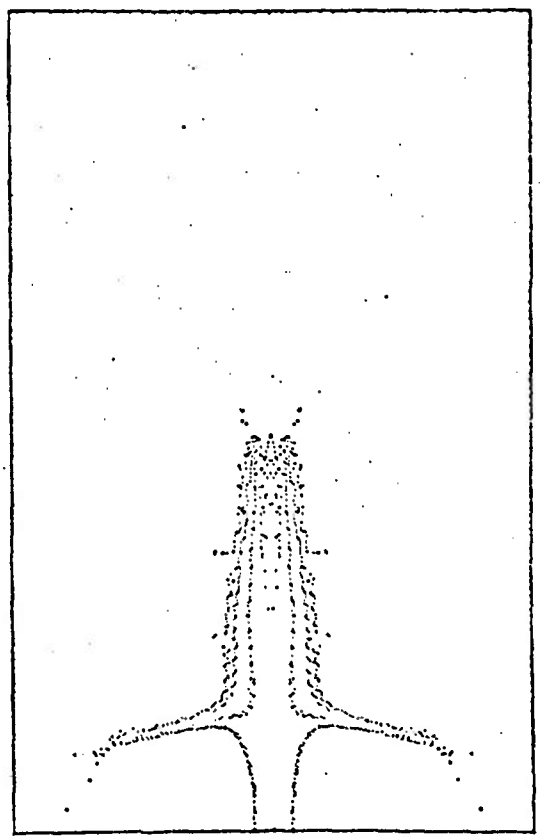
t = 18.3 μsec



t = 23.0 μsec



t = 28.0 μsec



t = 33.0 μsec

Fig. 5--BRL precision shaped charge.

cells (DX = DY = .12 cm) and the effects of strength were included.

Figure 6 shows the liner configuration at 10 μsec. The shaded regions shows cells which have not failed. For additional details, see Ref. [7].

7.3 THE COLLAPSE OF A FREE FLYING LINER

This problem was run during the early stages of developing BRLSC and is included as an example of mode 3. The liner was set up with an initial velocity of 3.3×10^5 cm/sec directed inward in the direction of the liner. The liner was copper, had a thickness of 0.27 cm, and had a half angle of 35.75 degrees. The grid was made up of square cells with (DX = DY = .05 cm). The effects of strength were not included.

Figure 7 shows the configurations at various times. For additional details, see Ref. [6].

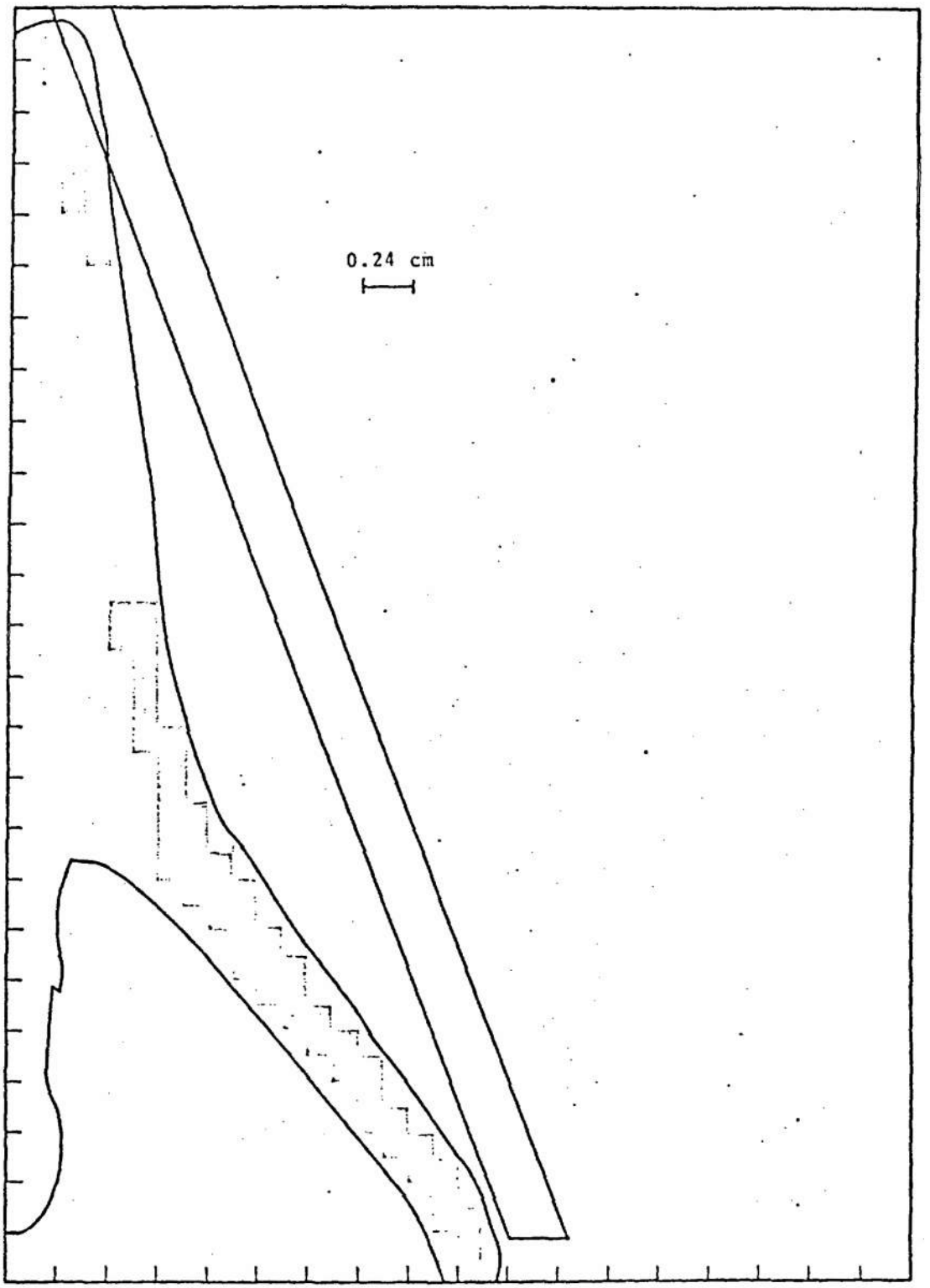
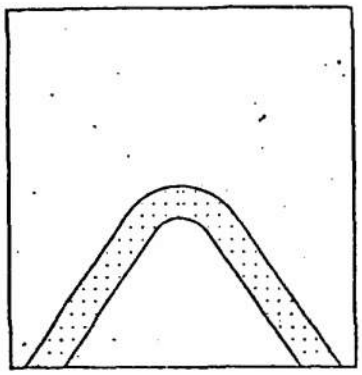
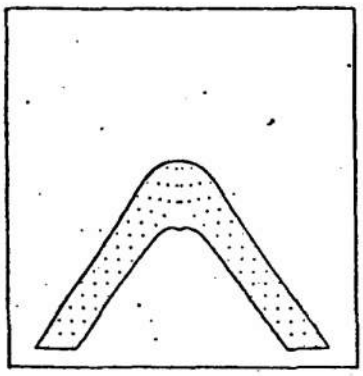


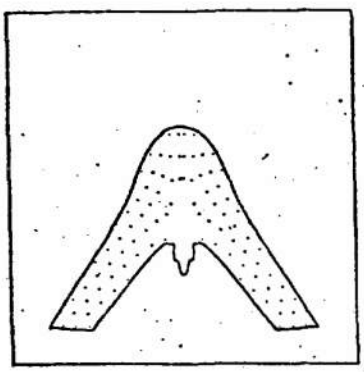
Fig. 6--Example of pressure boundary condition



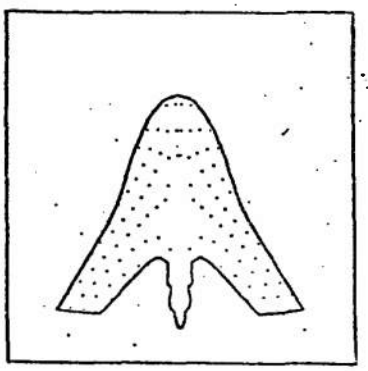
t = 0



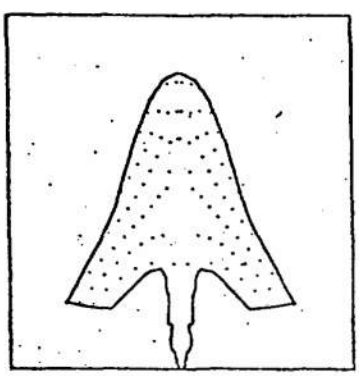
t = 0.6 μsec



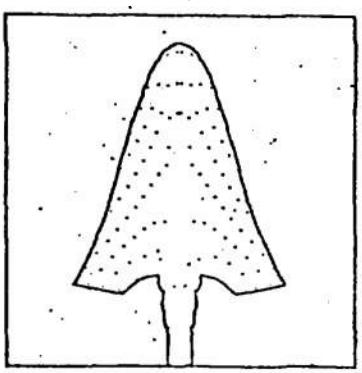
t = 1.1 μsec



t = 1.6 μsec



t = 2.0 μsec



t = 2.6 μsec

Fig. 7--Example of a Mode 3 calculation

VIII. USERS GUIDE TO THE BRLSC PROGRAM

This section of the report constitutes a users manual. It contains the information necessary to generate and run shaped charge problems with the BRLSC code and is divided into five parts. The first part gives a short description of some of the major problems encountered while writing BRLSC and what was done to overcome or minimize these problems. The second part contains a brief description of every subroutine in the BRLSC code. The third part gives some of the code's restrictions, the options available, and explains how to set up the input deck for generating and running shaped charge problems. In Section 8.4, the procedure for restarting problems is given and Section 8.5 is a dictionary of the more important variables used in BRLSC.

8.1 INTRODUCTORY REMARKS

BRLSC is basically the HELP[1] code which has been modified to allow it to handle shaped charge problems. While writing BRLSC, it became apparent that there were several main problems to overcome. A brief discussion of the problems and the modifications made to correct them follows.

8.1.1 Problem Generation

It was necessary to rewrite subroutine SETUP to allow shaped charge problems to be easily generated, giving the user a wide choice of possible materials, configurations, zoning, etc.

8.1.2 Thin Liners and Free Surface Cells

Since shaped charge problems involve thin liners moving diagonally through the computational grid, the majority of the cells which contain liner material are mixed cells, either containing liner material and high explosive or liner material and void. Two main problems became apparent when a thin liner was moved through the grid. First, free surface or underdense cells tended to be over-accelerated in PH1. This problem has been solved by rewriting the PH1 difference equations so that interface pressures are computed as an inverse density weighted average of the cell pressures. The second problem involved the realistic definition of the material density in free surface cells used in computing mass fluxes. This problem was overcome by computing volume fluxes as well as mass fluxes and updating the density of the material in free surface cells at the end of PH2. Also, the material densities are updated in PH1 by computing the change in volume due to the surrounding velocity field.

8.1.3 Computational Stability

In the initial solutions of shaped charge problems, it was observed that instabilities occurred in regions of the grid with low velocities. These instabilities often lead to unsatisfactory results. The stability of a calculation depends in part, on the effective viscosity which is the result of converting kinetic energy to internal energy during mass transport (PH2). If velocities are small, there is little mass flux between cells and, as a result, little effective viscosity. These instabilities were considerably reduced by computing a pseudo-viscous pressure term (i.e., artificial viscosity) which is included in the interface pressures computed in PH1.

8.1.4 Negative Internal Energies

Another major problem which arose during the early stages of the development of BRLSC involved negative internal energy. Negative internal energies were generated in one of three ways. First, when cells were over-accelerated in PH1, the increase in kinetic energy in the underdense "kicked" cell was offset by a decrease in internal energy in the cell(s) which did the "kicking". Secondly, if the mass fluxes out of a cell were greater than the mass in the cell (regardless of the mass fluxes into the cell), negative internal energies could result. Finally the internal energy of one material in a mixed cell could become negative when its momentum and energy were updated, even if the total cell internal energy was positive. This can occur in PH1 or PH2. The first of these problems was minimized by the inverse density weighting scheme for computing interface pressures in PH1. The second was cured by placing limitations on the mass fluxes out of cells. The third was solved by modifying the manner in which the internal energies of materials in mixed cells are incremented in PH1 and by insuring that all internal energies of materials in mixed cells have the same sign as the total cell energy at the end of PH1 and PH2.

8.1.5 Overheating of Cells

Certain cells in regions of very high velocity gradients tend to become overheated, i.e., their calculated internal energy is unrealistically high. This arises when the mass entering a cell is moving at a velocity extremely different from the mass already in the cell, so that too much kinetic energy is thermalized. To prevent this overheating from unrealistically vaporizing material, only the condensed form of the Tillotson equation of state is used.

8.1.6 Explosives

In order to run shaped charge problems, it was necessary to modify the code to handle explosives. This was done by adding subroutine EOSXPL which is called by EQST when computing pressures in cells containing the explosive. EOSXPL determines the location of the detonation front and whether the cell in question is behind, intercepted by, or ahead of the detonation front, modifies the equation of state for the explosive accordingly, and computes the pressure.

8.1.7 The Pressure Boundary Condition

Shaped charge problems can be run with BRLSC by applying time and position dependent pressure force along the outer surface of the liner. Subroutine PRESBC must be supplied the necessary information to compute the explosive's pressure, density, and internal energy for any point along the liner-explosive interface for any time. These values can be determined by a crudely resolved BRLSC calculation, a Lagrangian calculation, or from analytical approximations. BRLSC then computes the resulting liner collapse and jet formation. Since there is no actual explosive material in the grid, the cost of running a problem involving a well resolved liner is greatly reduced. Also, by omitting explosive material from the problem, an effective slip surface exists between the would-be explosive-liner interface.

8.2 SUBROUTINE DESCRIPTIONS

The following section contains a brief description of every subroutine used by the BRLSC code. Also included is a general flow diagram (Fig. 9) showing the inter-relationship between subroutines, and Table 3 lists all of the subroutines, which subroutines they call, and which subroutines they are called from.

ADJFLX: Subroutine ADJFLX calculates the mass and volume fluxes out of mixed cells which have lost a material interface and should be evaluacted of that material. It also initializes the mixed cell fluxes when called during the first pass through INFACE.

ADJSIE: Subroutine ADJSIE makes sure that all the specific internal energies assigned to materials in a mixed cell have the same sign as the total specific internal energy for the cell. It also insures that the sum of the cell's material masses and energies equal the total cell mass and energy.

APLYPR: Subroutine APLYPR can be used to apply a time and position dependent pressure boundary condition to a section of a material boundary. It identifies the cells to which the pressure is to be applied, calls PRESBC to determine the pressure, density and specific internal energy that the artificially applied material has at that point, adjusts the density of the material already in the cell to give the desired pressure, and fills the rest of the cell with the driving material.

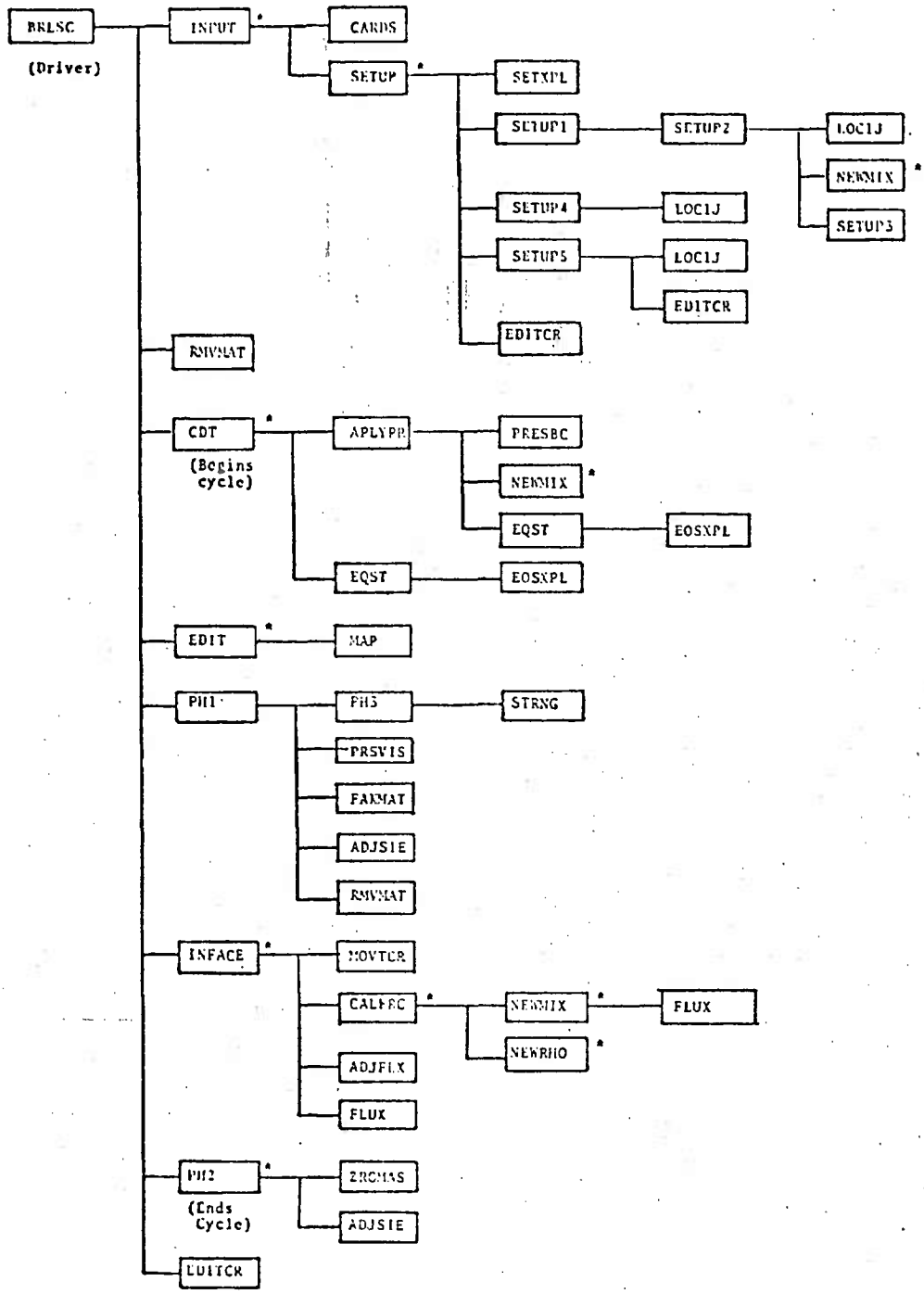


Fig. 9--General flow diagram of BRLSC program.

TABLE 3

SUBROUTINE REFERENCES

Subroutine	Calls	Is Called From
ADJFLX		INFACE
ADJSIE		PH1, PH2
APLYPR	EQST, NEWMIX, PRESBC	CDT
BRLSC	CDT, EDIT, EDITCR, INFACE, INPUT, PH1, PH2, RMVMAT	
CALFRC	ERROR, NEWMIX, NEWRHO	INFACE
CARDS		INPUT
CDT	APLYPR, EQST, ERROR	BRLSC
EDIT	ERROR, MAP	BRLSC, ERROR
EDITCR		BRLSC, SETUP, SETUP5
EOSXPL*		EQST, SETUP
EQST	EOSXPL	APLYPR, CDT
ERROR	EDIT	CALFRC, CDT, EDIT, INFACE, INPUT, NEWMIX, NEWRHO, PH2, SETUP
FAKMAT		PH1
FLUX		INFACE, NEWMIX
INFACE	ADJFLX, CALFRC, ERROR, FLUX, MOVTCR	BRLSC
INPUT	CARDS, ERROR, SETUP	BRLSC
LOCIJ		SETUP2, SETUP4, SETUP5
MAP		EDIT
MOVTCR		INFACE
NEWMIX	ERROR, FLUX	APLYPR, CALFRC, SETUP2

Table 3
Subroutine References (continued)

Subroutine	Calls	Is Called From
NEWRHO	ERROR	CALFRC
PH1	ADJSIE, FAKMAT, PH3, PRSVIS, RMVMAT	BRLSC
PH2	ADJSIE, ERROR, ZROMAS	BRLSC
PH3	STRNG	PH1
PRESBC		APLYPR
PRSVIS		PH1
RMVMAT		BRLSC, PH1
SETUP	EDITCR, ERROR, SETUP1 SETUP4, SETUP5, SETXPL*	INPUT
SETUP1	SETUP2	SETUP
SETUP2	LOCIJ, NEWMIX, SETUP3	SETUP1
SETUP3		SETUP2
SETUP4	LOCIJ	SETUP
SETUP5	EDITCR, LOCIJ	SETUP
STRNG		PH3
ZROMAS		PH2

*SETXPL is an entry point in EOSXPL

BLOCK: A block data element that defines normal density and the bulk sound speed of nineteen materials.

BRLSC: The overall cycling of the calculation is controlled by BRLSC, as shown in Fig. 9. It is the main routine of the code and calls INPUT, RMVMAT, CDT, EDIT, PH1, INFACE and PH2, in that order. If it is necessary to see the effects of each phase of the calculational cycle, BRLSC will respond to the input parameter INTER and call EDIT on print cycles after PH1 as well as after CDT. BRLSC also calls EDITCR and EXIT on the normal cessation of the calculation.

CALFRC: In subroutine CALFRC, the tracer particles that circumscribe each material package are followed and the intercepts with cell boundaries are determined. The location of each intercept is then used to determine the fractional cell areas for each material in each mixed cell. If a previously pure cell is intercepted, it is flagged mixed.

CARDS: Most of the input parameters stored in blank common are read by subroutine CARDS. The format of these input cards is described in Section 8.3.2.

CDT: A principal function of this routine is to compute a time step which ensures stability of the finite difference equations. This is done by finding the cell with the minimum of

(a) $\Delta X \Delta Y / (\Delta X |V| + \Delta Y |U|)$

(b) $\Delta X / C$

(c) $\Delta Y / C$

where ΔX is the radial dimension of the cell (cm), ΔY is the axial dimension of the cell (cm), $|U|$ is the absolute

value of the radial velocity of the cell (cm/sec), V is the absolute value of the axial velocity of the cell (cm/sec) and C is the local sound speed (cm/sec). For a polytropic gas the sound speed is computed as $\sqrt{\gamma p/\rho}$ and for other materials by the appropriate relation $C = C_0 + \bar{B}\sqrt{P}$ where P is the pressure in the cell and the coefficient, $\bar{B}$, is an input parameter. C is defined in BLOCK for nineteen materials as $\sqrt{A/\rho_0}$, where A is a coefficient in the solid equation of state. In a mixed cell the sound speed is given by a mass weighted average of the sound speeds of the materials in the cell. Each cycle CDT prints the column and row (I,J) of the cell controlling the time step as well as the maximum sound speed in the grid (MAXC), the maximum velocity in the grid (MAXUV) and the velocity and pressure cutoff values.

Another function of CDT is to equilibrate the pressures of materials in mixed cells using an iteration scheme that adjusts the material densities. A detailed discussion of this iteration method is found in Section 5. The pressures for pure cells are also updated in CDT by a call to the equation of state subroutine, EQST, with the density, energy and material code number of the cell (RHOW, ENERGY, N) passed through blank common.

When a pressure boundary condition is being applied to a material boundary, CDT calls subroutine APLYPR which computes the necessary densities and pressures in the cells that the surface intercepts. These cells are bypassed in the pressure iteration section of CDT.

EDIT: The periodic printing and writing on the restart tape are executed by subroutine EDIT. The frequency of printing and tape dumps is controlled by input parameters described in Section 8.3.3.

On every print cycle EDIT prints the mass, total energy, internal energy, kinetic energy, axial and radial momentum, and plastic work for each material package as well as for the entire grid. The changes in energy due to evaporation and losses out boundaries are also accounted for. The coordinates of the material tracers circumscribing each package are printed in cell units. Summary maps of the compression, pressure, velocities and internal energies are printed if the input parameter, MAPS, is non-zero. And finally, the pressure, velocities, internal energy, compression and stress deviators for all cells in the active grid are displayed on "long" EDIT prints and for each cell in the axis column on "short" EDIT print.

Another important function of EDIT is to compute the relative error in the total energy of the grid when summed over all the cells, and to check that this error does not exceed a limit specified by the input variable DMIN.

EDIT also senses when execution should stop and sets the exit flag, WFLAGL.

EDITCR: The coordinates of the interior tracers (XP, YP arrays) are printed by EDITCR. This subroutine is called from SETUP and at the end of every run.

EOSXPL: EOSXPL is called to compute pressures and the constant-energy compressibilities for ideal gasses and explosives. Gamma-law equation-of-state constants are given (Table 2) for eighteen explosives. If calculating the pressure for cells containing explosive material, the equation of state is modified for cells that are either cut by or are ahead of the detonation front. The modifications to the equation of state are such as to give zero pressures ahead of the detonation front without breaking down the pressure iteration. See Section 2.3 for further details.

An entry point labeled SETXPL is also included in EOSXPL. SETXPL is called in setup and returns the gamma, detonation velocity, initial density, and specific available energy for the explosive being set up.

EQST: The equation of state constants for nineteen materials are stored in DATA statements in EQST. (These constants are displayed in Table 1.) Given a code number for specifying the material, a density and an energy, EQST computes a pressure and a constant-energy compressibility. A more detailed discussion of the equation of state is given in Section 2.3. EQST is called by CDT to compute pressures of pure cells as well as of materials in mixed cells. EQST is also called from APLYPR when iterating to find the density of material in a cell which is to have a pressure boundary condition applied to it.

ERROR: This subroutine is called in the event that certain error conditions are violated, e.g., the energy sum error exceeding the specified limit. ERROR prints a message identifying the general location of the error condition, lists the Z-block variables (first 150 words of blank common), calls EDIT to do a long print and tape dump, and then calls exit.

FAKMAT: If a pressure boundary condition is being applied, FAKMAT identifies all interfaces between void cells and cells which have had their pressures defined by APLYPR. The interface pressures are redefined in a manner that allows these interfaces to be treated as if they were transmittive boundaries. The total theoretical energy is then updated to reflect the work done at the interfaces.

FLUX: The mass and volume fluxes across the right and top boundaries of a mixed cell for each material in that cell are computed in FLUX. These fluxes are stored in the SAMPY, SAMMP, VOLRT and VOLTP arrays and executed in subroutine PH2 which does the actual transport of material across all cell boundaries. FLUX uses the position of the material interfaces to compute the fluxes of the various materials in the cell. See Section 4.5 for a more complete description of transport from mixed cells.

INFACE: The tracer particles that circumscribe each material package are moved by calling MOVTCR from INFACE. Subroutine CALFRC is then called by INFACE to determine where the interfaces cut cell boundaries and to compute the fractional areas for each material at these interfaces. For a given cycle, INFACE senses which cells become mixed and which become pure. INFACE also calls FLUX to determine the mass and volume fluxes across mixed cell interfaces and calls ADJFLX to initialize the flux arrays and to set fluxes to remove material from mixed cells which become pure.

INPUT: Instructions for running problems are interpreted by INPUT which can either start or restart a calculation. It calls SETUP and CARDS, as necessary, to prescribe the initial conditions and to read the input deck.

LOCIJ: This routine is used to identify the column or row location of a tracer point whose coordinates are in centimeter units. SETUP calls LOCIJ when converting tracer coordinates to cell units.

MAP: This subroutine is called by EDIT when the input parameter MAPS is non-zero. It displays the properties of each cell in the active grid using an alphabetic scale. [On cycle 0 it presents the entire (IMAX by JMAX) grid.] One

obtains contour maps of the compression, pressure, radial and axial velocities, and internal energy. Since the compression of mixed cells is not computed, asterisks are displayed for mixed cells in the compression map. The scale of each map is adjusted according to the current minimum and maximum values of each property.

MOVTCR: Subroutine MOVTCR moves the interface and interior tracers by looking at a control area surrounding each tracer and finding which cells this control area overlaps and the overlap areas. A density-area weighted velocity is then computed using the densities and velocities of the cells overlapped by the control area. Each tracer is then moved with the resulting average velocity.

NEWMIX: When a pure cell K becomes mixed, NEWMIX assigns to it a location M in the mixed cell arrays (SIE, XMASS, RHO, etc.) The flag of cell K is redefined so as to associate the K and the M indices (MFLAG(K) = M + 100). The fact that MFLAG(K) is greater than 100 indicates cell K is a mixed cell. Otherwise, if cell K were pure, MFLAG(K) would be equal to the number of the package that contained cell K.

NEWMIX is called from CALFRC (called from INFACE which is usually subcycled) and from SETUP. If cell K becomes mixed after the first subcycle of INFACE, NEWMIX calls FLUX to bring the definition of the flux variables for cell K to the current time. (See Section 4.6 for further discussion of mixed cells.)

NEWRHO: When the material N interface first enters a cell, CALFRC calls subroutine NEWRHO to define the density of material N for cell K by looking at the density of material N in the neighboring cells closest to the interface.

(This density value, stored in the RHO array, is updated in CDT when pressures are equilibrated at the beginning of each cycle. If the cell is a free surface cell, the densities are updated in PH1 by looking at the velocity field and in PH2 by keeping track of mass and volume fluxes.)

PH1: The effect of the pressures and deviator stresses in updating the velocities and internal energies is computed in PH1. [See Section 2.2.2.] The effect of pressures applied at material boundaries and the updating of the mass densities in free surface cells are also handled in PH1.

PH2: Mass transport and the associated flux of momentum and energy are accounted for in PH2. After the transport has been completed, PH2 corrects for negative mass quantities in mixed cells by calling subroutine ZROMAS. Before printing the symbolic map which displays the material package numbers and mixed cell locations, PH2 redefines the flags of cells that have become pure.

PH3: The cell-centered deviator stresses are updated each cycle in PH3. (The effect of these deviator stresses on velocities and internal energies is computed in PH1.) PH3 calls STRNG to compute the yield strength of the material in a cell. If the effects of strength are to be omitted (CYCPH3 $\leq$ 0.), PH3 insures that all the deviator stresses are zero and returns to PH1.

PRESBC: If a pressure boundary condition is desired, the user must supply this subroutine which computes a pressure, density and energy for any given time and location in the grid. See Section 6 for a more detailed explanation.

PRSVIS: Subroutine PRSVIS is called from PH1 and computes a pseudo-viscous pressure which is added to the interface pressure terms. This artificial viscosity helps minimize instabilities in low velocity stagnation regions.

RMVMAT: If a pressure boundary condition is being used, RMVMAT (which is called whenever a problem is being restarted and at the end of PH1) removes any mass and energy which was added by APLYPR and updates the total theoretical energy.

SETUP: This routine generates the shaped charge problems to be run. It defines the X, Y, DX, DY and TAU arrays for variable as well as constant zoning in either cylindrical or rectangular geometries. The properties of material packages are determined by reading the INPUT cards. SETUP1 is called to fill the cells with the necessary material, SETUP4 is called to place the interface tracers, and SETUP5 is called to place the interior tracers. The total theoretical energy is set equal to the total energy in the problem and a tape dump is written.

SETUP1: After SETUP has read the INPUT cards, SETUP1 is called. SETUP1 first checks to make sure that the INPUT data defines an acceptable shaped charge configuration and then calls SETUP2 to determine MFLAG and compute the mass in every cell. SETUP1 then sets the U, V, and AIX arrays for each cell.

SETUP2: SETUP2 sets the MFLAG, AMX, XMASS, and RHO arrays for each cell in the grid. The mass for each material is computed by calling SETUP3 to determine the partial volume each material occupies in a cell.

SETUP3: SETUP3 determines if a cell is void, pure, or mixed and returns the partial volume occupied by each material and the void in the cell.

SETUP4: The interface tracers (TX, and TY arrays) are placed around the material packages and the void by SETUP4.

SETUP5: The passive interior tracers (XP and YP arrays) are placed by subroutine SETUP5.

STRNG: The yield strength of the material in a cell is computed by STRNG. (The strength constants for the liner material are defined by input cards when the problem is generated.) The yield strength of the material in a mixed cell is a volume weighted average of the yield strengths of the various materials in the cell. STRNG is called from PH3.

ZROMAS: If PH2 transports more mass out of a mixed cell than is in the cell, ZROMAS is called. ZROMAS determines which cells received the excess mass. Enough material is removed from these cells to bring the total mass, momentum and energy of the over-evacuated material in the cell back to zero.

8.3 GENERATING PROBLEMS

8.3.1 General Capabilities and Limitations

The procedure for setting up a problem to be run by BRLSC has been simplified to allow problems to be defined as easily as possible. Many of the variables have predetermined default values assigned to them so that it is not necessary to enter them unless they are to be changed.

8.3.1.1 Modes

BRLSC is capable of running problems in any of three basic modes. They are:

1. In Mode 1, complete shaped charge problems are set up and run. Both the explosive and the liner are in the grid and the problem can be run as far in time as desired with no additional input. See Section 7.1 for an example of a problem run in Mode 1.

2. In Mode 2, only the liner is set up in the grid. The explosive driving pressures are applied along the outside surface of the liner in the form of a time and position dependent pressure boundary condition. The pressure, density and specific internal energy of the driving explosive are entered into the calculation each cycle from subroutine PRESBC. The user must supply this subroutine for Mode 2 calculations. The values returned can be determined in any way the user wishes: analytical equations, table lookup, another calculation (Eulerian or Lagrangian), etc. The resulting liner motion is then calculated. See Section 7.2 for an example of Mode 2.

3. In Mode 3, the liner only is set up and given an initial velocity. Mode 3 can be used to investigate such problems as an initially free flying plate being driven into the plane of symmetry. See Section 7.3 for an example of Mode 3.

8.3.1.2 Restrictions and Limitations

When setting up a problem, several restrictions and limitations must be kept in mind. These are:

1. No more than two material packages may be set up, one for the liner and, if running in Mode 1, one for the explosive.
2. All the material packages must be entirely contained in the grid.
3. The half angle of the liner must be between five and eighty-five degrees.
4. If the liner is set up with a round tip, the inside radius of the tip must be less than the inside radius of the base of the liner.
5. When setting up a problem in Modes 1 or 2, the initial radial velocity must be zero.
6. The left-hand boundary of the grid (i.e., the axis) is always considered to be reflective. The other three boundaries are always transmittive.
7. In Mode 1, the top of the explosive package must be above the tip of the liner, the radius of the explosive package must be greater or equal to the outside radius of

the base of the liner, and the axial position of the bottom of the explosive is forced to be equal to that of the liner.

8. The diagonal dimension of every cell which contains liner material should be less than the thickness of the liner. Best results are obtained if all cells initially containing liner material are square, i.e., DX = DY.

9. It is suggested that when setting up a problem in Modes 1 or 2, that the initial axial velocity be zero.

8.3.1.3 Capabilities

The capabilities of BRLSC for setting up and running shaped charge problems are generalized below.

1. Choice of operating mode:
   - Two materials, i.e., liner and explosive
   - Liner and pressure boundary condition
   - Liner only
2. Choice of liner material:
   - Tungsten
   - Copper
   - Iron
   - Aluminum
   - Beryllium
   - Titanium
   - Nickle
   - Molybdenum
   - Thorium
   - Lead

3. Choice of Explosives:

   - Baratol
   - Comp B, Grade A
   - Comp B-3
   - Cyclotol (77/23)
   - Datb
   - HMX
   - LX-01-0
   - LX-04-1
   - LX-07-0
   - Nitroglycerine
   - Nitromethane
   - Octol (77.6/22.4)
   - PBX-9010
   - PBX-9011
   - PBX-9404-03
   - PETW
   - RDX
   - TNT

4. Choice of liner half angle, thickness, base radius, and tip geometry (round or pointed).

5. Choice of explosive dimensions.

6. Choice of spherical or plane detonation front. If spherical, choice of initial radius of curvature.

7. Option of including or not including the effects of material strength in the calculation.

8.3.2 Format of Input Cards

A BRLSC problem is generated by three kinds of input data:

1. The identification header card read by INPUT that contains alphanumeric symbols in columns 2 through 72.
2. The input data read by subroutine CARDS that defines variables in the Z-block (the first 150 words of blank common).
3. The input data read by subroutine SETUP that defines the DX, DY arrays when either or both are variable and the boundaries and properties of the material packages.

The input cards read by CARDS use the following format:

(I1)	(I5)	(I1)	(E9.4)	(E9.4)
Col. 1	Cols. 2-6	Col. 7	Cols. 8-16	Cols. 17-35 etc.
L	M	N	Z(M)	Z(M+1)

The value of L for each input variable is listed in the discussion that follows. When L=0 the variable defined is typed real. When L=2, the variable defined is typed integer. When L=1 the variable defined is typed real and the card is the last one to be read until CARDS is called again. The value of M is the location in blank common of the variable being defined in Cols. 8-16; this location number is also listed below for each input variable. The value of N indicates how many consecutively stored variables of the same type are defined by a card (usually N=1). Z(M) must be punched with an E format even when it is defining an integer variable.

The format of the cards read by SETUP varies and is described in the following discussion of the input variables.

8.3.3 Description of INPUT Variables

The following list of INPUT variables is ordered as the BRLSC setup INPUT deck should be ordered. These variables are broken into four groups. The first three groups of cards are read by CARDS. The fourth group is read by SETUP and the last dummy card is read by CARDS.

The first group contains the cards which must be defined in order to run a problem. The second group lists the variables which have default values assigned them and which are generally omitted unless these default values are to be changed. The third group contains variables which are either calculated or zero at setup time. Except in rare instances when restarting a problem (i.e., switching to a new dump tape, etc.), there is no need to ever input or change them.

8.3.3.1 Group 1 (Most Common Variables Read by CARDS)

Variable Name	Column One Flag	Location in Blank Common	Definition
PK(1)	1	151	Problem number. Any number from .0001 to 99.9999. Should be identical to PROB. This is the second input card of a restart as well as a setup deck. (The first card is the identification header card.)
PROB		1	Problem number [same as PK(1)].

Variable Name	Column One Flag	Location in Blank Common	Definition
NFRELP	2	5	Gives frequency of "long" EDIT prints which gives velocities, energy, compression and stresses for all cells in active grid. A "short" EDIT gives this information only for the axis column. When NFRELP=2, every second EDIT print is "long".
NDUMP7	2	6	Gives frequency of restart tape dumps. Program will dump only when EDIT prints. If NDUMP7=5, a restart dump will be made every 5th time EDIT prints.
ICSTOP	2	7	Gives cycle at which execution will stop if the user wants to specify a cycle rather than a time on which to stop. If stopping on time omit this card.
IGM	2	21	When IGM=0. code uses cylindrical coordinates. When IGM=1., code uses plane coordinates.
IMAX	2	33	The number of columns in the grid.
JMAX	2	35	The number of rows in the grid.
MAPS	2	42	When MAPS > 0., part of the EDIT print is a set of symbolic maps of the compression, pressures, velocities, and specified internal energies of cells in the active grid.
PRDELT		45	The time (sec) between EDIT prints. If printing on cycle intervals omit this card.

Variable Name	Column One Flag	Location in Blank Common	Definition
IPCYCL	2	49	The number of cycles between EDIT prints. If printing on time intervals omit this card.
CYCPH3		70	The number of passes through subroutine PH3 (strength phase) in one time step. Usually CYCPH3 = 2., but larger values can help to dampen oscillations. Omit this card when the calculation is pure hydro (no strength effects).
NMXCLS	2	73	The maximum number of mixed cells to exist in the grid at any one time during the calculation. Consult the dimensions of the mixed cell arrays in MXCELL COMMON and BLANK COMMON.
NTPMX	2	78	Used in SETUP to compute the number of tracers to be placed around each material package. The code will place the tracers in such a way that no package will contain more than NTPMX tracers. This maximum cannot be greater than the dimensions of the TX and TY arrays.
INTER	2	87	A special editing flag for debugging. When INTER = 1., EDIT prints after PH1 as well as after CDT on print cycles. When INTER = 7., PH2 prints energy totals after updating each cell. The later option is in addition to the extra EDIT prints and involve many pages of output.

Variable Name	Column One Flag	Location in Blank Common	Definition
NODUMP	2	96	When NODUMP = 1., EDIT will not write any tape dumps. (This flag overrides the NDUMP7 option, but does not prevent SETUP from writing the cycle 0 dump.)
DXF		136	The x-dimension of cells (cm) when the grid has constant zoning in the x-direction. Omit this card if the x-dimension of cells varies.
DYF		137	The y-dimension of cells (cm) when the grid has constant zoning in the y-direction. Omit this card if the y-dimension of cells varies.
TSTOP	1	50	The time (sec) at which the calculation will stop. This card (with a "1" in column one) should not be omitted even when stopping on a specified cycle, and should always be the last card of a restart deck.

8.3.3.2 Group 2 (Variables with Default Values Assigned)

Variable Name	Column One Flag	Location in Blank Common	Definition
IPR	2	15	Maximum number of iterations CDT will perform when attempting to equilibrate the pressures of materials in a mixed cell. If the pressures are not within an epsilon (PRCNT) of the average pressure after IPR iterations, an error exit occurs. (DEFAULT = 30)
PRCNT		16	Convergence minimum for the pressure equilibration of materials in a mixed cell. All pressures, P_i, must satisfy the following: $\left\|\left(P_{av}-P_i\right)/P_{av}\right\| <$PRCNT. (DEFAULT=.001)
DMIN		24	The maximum relative error in the energy sum that the user wants to tolerate. The error is computed as follows: $\left\|\left(\sum_{K=1}^{KMAX} E_k - ETH\right)/ETH\right\|$ where E_k is total energy of cell K and ETH is theoretical energy in the grid--computed in SETUP and updated in PH1, PH2, APLYPR and RMVMAT. (DEFAULT = 10^{-3})

Variable Name	Column One Flag	Location in Blank Common	Definition
CYCMX		69	The number of passes through subroutine INFACE in one time step to minimize transport noise near interfaces. Usually CYCMX = 2, but when calculation costs permit, CYCMX = 8 is a good maximum. (DEFAULT = 2)
PMIN		86	A pressure cutoff (DEFAULT = 5×10^6).
ROEPS		110	A round-off epsilon used to define cutoffs in the calculation. (DEFAULT = 10^{-5})
FINAL		113	The final value of the stability fraction used in determining the time step. (See STAB)(DEFAULT = .4)
STAB		139	The initial value of the "stability fraction" for the calculation of DT. If FINAL=0., STAB is constant. Otherwise its value increases from the input value to FINAL in a geometric progression. (DEFAULT = .001)
DTMIN		144	The minimum value for the time step. The program gives an error exit if CDT calculates a $\Delta t <$ DTMIN. (DEFAULT = 10^{-11})
BBAR		149	A constant used in calculation of local sound speed of all materials except ideal gases. $C = C_0 + BBAR \cdot (\sqrt{P})$. (DEFAULT = .5)

8.3.3.3 Group 3 (Seldom Used Variables)

Variable Name	Column One Flag	Location in Blank Common	Definition
KUNITR	2	14	The tape unit INPUT will read from. KUNITR will be set equal to 7 unless defined by this input card.
KUNITW	2	17	The tape unit EDIT and SETUP will write on. KUNITW will be set equal to 7 unless defined by this input card.
CVIS		27	A flag that describes the boundary condition at the bottom of the grid. If CVIS=0., the boundary will be reflective. If CVIS=-1., the boundary will be transmittive.
NUMSCA	2	43	The number of times the cycle or time interval between EDIT prints is increased. (See PRLIM)
PRLIM		44	The time or cycle at which the EDIT print frequency is changed. Example: you wish to print every 10^{-8} sec until T = 10^{-7} sec; and every 10^{-7} sec until T = 10^{-6} sec, and every 10^{-6} sec thereafter. Set: PRDELT = 10^{-8} IPCYCL = 0. PRLIM = 10^{-7} PRFACT = 10 NUMSCA = 2. NOTE: When PRDELT is increased by a factor, PRLIM is also increased by the same factor for the next rescaling. If you want a constant print interval omit NUMSCA, PRLIM, PRFACT.

Variable Name	Column One Flag	Location in Blank Common	Definition
PRFACT		46	The factor by which the print interval (PRDELT or IPCYCL) and the print limit (PRLIM) are increased. (See PRLIM)
I1	2	47	The number of columns in the grid that have non-zero velocities or energies plus 2. I1 and I2 define the "active" grid. (Most calculations are done inside the active grid.)
I2	2	48	The number of rows in the grid that have non-zero velocities or energy plus 2.
IVARDY	2	54	When the grid is variably zoned in the y-direction (DX's not constant), IVARDY=1. When the grid has constant zoning in the y-direction (DYF>0.), IVARDY=0.
N6	2	56	This parameter causes the program to set negative pressures to zero in the rows of the grid below J = N6. Omit this card if you want to allow negative pressures everywhere in the grid. If you want to set negative pressures to zero everywhere, set N6 = 10^4.
GAMMA		62	(a+1.) in gamma-law equation of state. Used only for an ideal gas.
NMAT	2	68	The number of material packages, exluding the void package. The maximum number of packages is two.

Variable Name	Column One Flag	Location in Blank Common	Definition
IVARDX	2	83	When the grid is variably zoned in the x-direction (DX's not constant), IVARDX=1. When the grid has constant zoning in the x-direction (DXF>0), IVARDX=0.
EMIN		85	The minimum specific internal energy of an ideal gas to be used in the pressure iteration. Usually EMIN = 10^6.
DTFIX		143	Gives the maximum DT to be used in the calculation. If DTFIX>DMIN, then DT=min(DT,DTFIX) where DT is computed each cycle by CDT. Omit this card if no maximum is to be place on the time step.

8.3.3.4 Group 4 (Input Read by SETUP)

1. Defining Cell Dimensions When Variable. User can specify variable DY and/or DX values. In the case that both are variable, the DY array is defined first. Both arrays are read using the following format:

Variable Name	Columns	Definition
NT(I), I=1,4	1-4 5-8 9-12 13-16	NT(I) is the number of zones that have dimension TEMP(I). When all DY's are defined, set next NT=999. Likewise for DX's.
TEMP(I),I=1,4	21-30 31-40 41-50 51-60	NOTE: When DY's are variable, exactly JMAX DY's must be defined. Likewise, exactly IMAX DX's must be defined.

2. Defining the Liner.

Variable Name	Card Number	Columns (Format)	Definition
MODE	1	1 (I1)	If MODE=1, both the liner and explosive are set up. If MODE=2, only the liner is set up and a pressure boundary condition will be applied along the outer free surface. If MODE=3, only the liner will be set up with some initial velocity. See Section 8.3.1.1 for details.
MAT(1)	2	1-5 (I5)	Material code number for the liner $1 \leq MAT(1) \leq 10$. (i.e., if MAT(1)=2, the liner is copper.) See Table 1, Section 2.3.1 for list of liner materials available.

Variable Name	Card Number	Columns (Format)	Definition
NTHCK	2	6-10 (I5)	Indicates the number of interior tracers to be placed across the thickness of the liner. If no interior tracers are desired, NTHCK=0.
ALPHA	2	11-20 (E10.2)	ALPHA is the half angle of the top of the liner. $5° \leq$ ALPHA $\leq 85°$.
YTIPI	2	21-30 (E10.2)	YTIPI is the Y coordinate of the inside tip of the liner. If YTIPI > 0., the tip is placed YTIPI cm from bottom of grid. If YTIPI < 0, the tip is placed at |YTIPI| cells from the bottom of the grid.
RTIPI	2	31-40 (E10.2)	Radius in cm of the inside of the tip of the liner. If RTIPI < 0, the liner is set up with a pointed tip.
THICK	2	41-50 (E10.2)	Thickness (cm) of the liner.
RLINI	2	51-60 (E10.2)	Radius (cm) of the inside of the base of the liner.
UUR(1)	3	1-10 (E10.2)	Initial radial velocity of liner (cm/sec). UUR(1) will be set =0. in Modes 1 and 2.
VVA(1)	3	11-20 (E10.2)	Initial axial velocity (cm/sec) of entire shaped charge (usually =0. in Modes 1 or 2).
SSIEN(1)	3	21-30 (E10.2)	Initial specific energy (ergs/g) of liner material.
RHOIN(1)	3	31-40 (E10.2)	Initial density (g/cm^3) of liner material.

Variable Name	Card Number	Columns (Format)	Definition
CZERO(1)	4	1-10 (E10.2)	Y_0 — used to determine yield strength of the liner material.
STK1(1)	4	11-20 (E10.2)	C — Y.S. = $(Y_0 + C*P)(1-E/E_0)$ where P = pressure and E = specific internal energy.
STEZ(1)	4	21-30 (E10.2)	E_0
RMU(1)	4	31-40 (E10.2)	Rigidity modulus for liner material.
AMDM(1)	4	41-50 (E10.2)	Failure criterion for liner material. If the compression of the liner material in a cell is less than AMDM, the cell has failed and all tensile stresses are set to zero.

The following card is used only if MODE = 1. It describes the explosive package.

MATXPL	5	1-5 (I5)	The absolute value of MATXPL defines the type of explosive to be used. (See Table 2, Section 2.3.2 for list of available explosives). If MATXPL is > 0, a plane detonation front will be used. If MATXPL < 0, a curved detonation front is used.
XPLRAD	5	11-20 (E10.2)	If the problem is being set up to run with a plane detonation front, XPLRAD will be set = 0. If running with a curved detonation front, XPLRAD is the initial radius (cm) of the detonation front. (If XPLRAD = 5., the explosive was detonated at a point 5 cm above the top of the explosive package.)
RITXPL	5	21-30 (E10.2)	The radius (cm) of the outside of the explosive.

Variable Name	Card Number	Columns (Format)	Definition
TOPXPL	5	31-40 (E10.2)	The distance (cm) from the outside tip of the liner to the top of the explosive.
EMIN	5	41-50 (E10.2)	The minimum specific internal energy (ergs/g) of the explosive to be used in the pressure iteration. If EMIN is entered as 0, the program will give it a value of 10^6.

The last card on the setup deck (read by CARDS) is

Variable Name	Column One Flag	Location in Blank Common	Definition
EMOB	1	150	Dummy end card of SETUP deck. Omit from restart deck. EMOB = 0.

8.3.4 Sample Input Deck for Setting up a BRLSC Problem

The input deck for setting up a mode 1 shaped charge problem is listed below. This problem has been set up and run to a time of one microsecond on the version of BRLSC listed in this report.

```
                                        TEST OF MODE 1
1   151 1 1.1
      1 1 1.1
2     5 1 1000.0
2     6 1 1.0
2    37 1 20.0
2    75 1 40.0
2    47 1 1.0
     65 2 5.0    -07
2    77 1 200.0
2    79 2 100.0
2    96 1 1.0
1    50 3 1.0    -05
   2   36    2 999      0.10        0.05        0.10
  18    2 999            0.05        0.10
1
      2      021.0       1.15        0.1414      0.1414      0.0
0.0           0.0         0.0         0.0
0.0           0.0         0.0         0.0         0.07
    -2        0.0         0.75        0.5         0.0
1  15010.0
```

The following pages show part of the printed output from the sample problem whose input deck is described above. The calculation was for a shaped charge with a .1414 cm thick copper liner and a Comp B explosive. The half-angle of the liner was 21 degrees, the radius of the base of the liner was .4 cm, and the radius of the tip of the liner was .1414 cm. A curved detonation front was employed and strength effects were ignored.

PROBLEM	TIME	CYCLE	TOT.EN.THEOR.	MAX.REL.ERROR-CYCLE		IE SET TO ZERO-PH2	ELASTIC PLASTIC WORK
1.1000	1.0000000-06	34	1.8127966+11	-9.7158167-07	33	3.1513300+03	0.0000000

PACKAGE NO.	IE	KE	TOT.EN. (SUM)	MASS	MV	MV(POSITIVE)	MU	PLASTIC-WORK
1	1.4437721+08	2.9573392+08	4.4011114+08	2.3059853+00	-1.4151593+04	0.0000000	-1.5932548+03	0.0000000
2	1.6214173+11	1.0697690+10	1.6083939+11	3.6008904+00	1.4151582+04	7.9701294+04	1.2913009+05	0.0000000
TOTALS	1.6226607+11	1.0993423+10	1.8127950+11	5.9068757+00	-1.1352539-02	7.9701294+04	1.2753603+05	0.0000000

BOUNDARY	BOTTOM	RIGHT	TOP	EVAPORATED
MASS OUT	0.0000000	0.0000000	0.0000000	2.2737368-13
ENERGY OUT	0.0000000	0.0000000	0.0000000	4.8828125-04
MU OUT	0.0000000	0.0000000	0.0000000	9.2426825-09
MV OUT	0.0000000	0.0000000	0.0000000	-1.0726839-08
WORK DONE	0.0000000	0.0000000	0.0000000	

CELL-COORDINATES OF TRACERS FOR EACH MATERIAL PACKAGE

PACKAGE 1

N	X	Y	N	X	Y	N	X	Y	N	X	Y	N	X	Y
1	.00	20.75	2	.47	20.71	3	.93	20.62	4	1.36	20.47	5	1.76	20.22
6	2.11	19.91	7	2.41	19.56	8	2.63	19.15	9	2.82	18.68	10	3.01	18.21
11	3.19	17.74	12	3.38	17.26	13	3.56	16.78	14	3.75	16.30	15	3.93	15.82
16	4.12	15.33	17	4.30	14.85	18	4.49	14.37	19	4.67	13.89	20	4.86	13.41
21	5.04	12.93	22	5.23	12.44	23	5.41	11.96	24	5.60	11.48	25	5.78	11.00
26	5.97	10.52	27	6.15	10.04	28	6.34	9.56	29	6.52	9.07	30	6.71	8.59
31	6.89	8.11	32	7.08	7.63	33	7.26	7.15	34	7.45	6.67	35	7.63	6.19
36	7.82	5.70	37	8.00	5.22	38	8.50	5.22	39	9.01	5.22	40	9.51	5.22
41	10.02	5.22	42	10.52	5.22	43	11.03	5.22	44	10.84	5.71	45	10.66	6.19
46	10.47	6.67	47	10.29	7.16	48	10.10	7.64	49	9.92	8.12	50	9.73	8.60
51	9.55	9.09	52	9.36	9.57	53	9.17	10.05	54	8.99	10.54	55	8.80	11.02
56	8.62	11.50	57	8.43	11.99	58	8.25	12.47	59	8.06	12.95	60	7.88	13.44
61	7.69	13.92	62	7.51	14.40	63	7.32	14.88	64	7.13	15.37	65	6.95	15.85
66	6.76	16.33	67	6.58	16.82	68	6.39	17.30	69	6.21	17.77	70	6.03	18.24
71	5.84	18.70	72	5.66	19.15	73	5.49	19.59	74	5.30	20.04	75	5.11	20.45
76	4.89	20.86	77	4.63	21.23	78	4.34	21.59	79	4.01	21.92	80	3.66	22.22
81	3.27	22.50	82	2.85	22.75	83	2.41	22.96	84	1.97	23.13	85	1.50	23.28
86	1.00	23.41	87	.50	23.49	88	.00	23.51	89	.00	20.75			

PACKAGE 2

N	X	Y	N	X	Y	N	X	Y	N	X	Y	N	X	Y
1	.00	23.51	2	.50	23.49	3	1.00	23.41	4	1.50	23.28	5	1.97	23.13
6	2.41	22.96	7	2.85	22.75	8	3.27	22.50	9	3.66	22.22	10	4.01	21.92
11	4.34	21.59	12	4.63	21.23	13	4.89	20.86	14	5.11	20.45	15	5.30	20.04
16	5.49	19.59	17	5.66	19.15	18	5.84	18.70	19	6.03	18.24	20	6.21	17.77

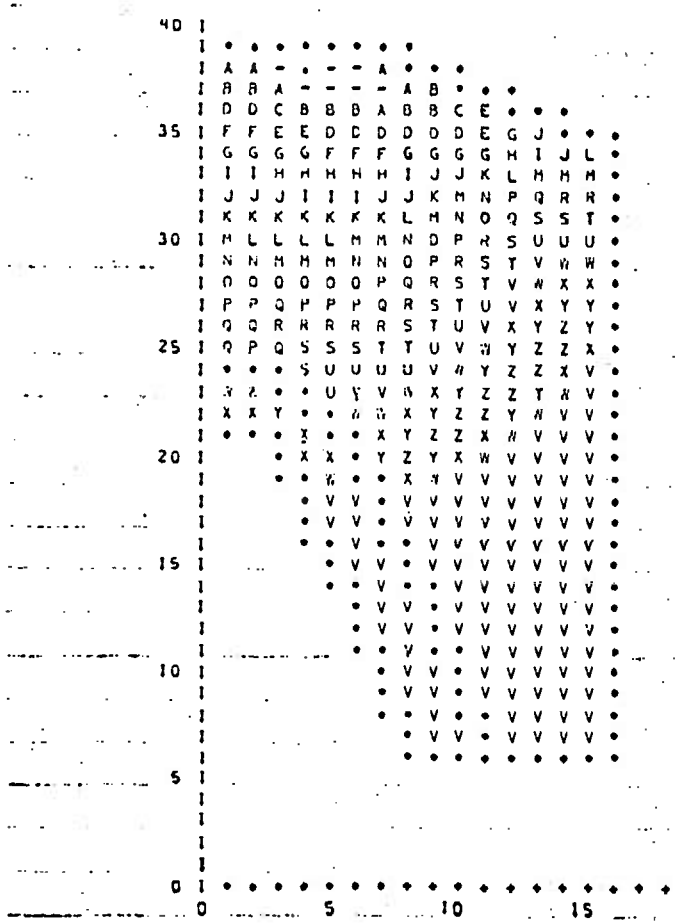
21	6.39	17.30	22	6.58	16.82	23	6.76	16.33	24	6.95	15.85	25	7.13	15.37
26	7.32	14.88	27	7.51	14.40	28	7.69	13.92	29	7.88	13.44	30	8.06	12.95
31	8.25	12.47	32	8.43	11.99	33	8.62	11.50	34	8.80	11.02	35	8.99	10.54
36	9.17	10.05	37	9.36	9.57	38	9.55	9.09	39	9.73	8.60	40	9.92	8.12
41	10.10	7.64	42	10.29	7.16	43	10.47	6.67	44	10.66	6.19	45	10.84	5.71
46	11.03	5.22	47	12.02	5.22	48	13.01	5.22	49	14.01	5.22	50	15.00	5.22
51	15.00	6.24	52	15.00	7.27	53	15.00	8.29	54	15.00	9.31	55	15.00	10.33
56	15.00	11.35	57	15.00	12.37	58	15.00	13.40	59	15.00	14.42	60	15.00	15.44
61	15.00	16.46	62	15.00	17.48	63	15.00	18.50	64	15.00	19.53	65	15.00	20.55
66	15.00	21.57	67	15.00	22.59	68	15.00	23.61	69	15.02	24.63	70	15.07	25.63
71	15.16	26.63	72	15.26	27.63	73	15.37	28.64	74	15.48	29.66	75	15.57	30.69
76	15.62	31.76	77	15.63	32.94	78	15.67	34.19	79	14.63	34.34	80	13.67	34.74
81	12.41	35.15	82	11.96	35.60	83	11.12	36.06	84	10.26	36.54	85	9.40	37.04
86	8.47	37.51	87	7.54	38.00	88	6.49	38.21	89	5.38	38.39	90	4.17	38.55
91	2.83	38.66	92	1.36	38.65	93	.00	38.60	94	.00	23.51			

FREE SURFACE TRACERS

N	X	Y	N	X	Y	N	X	Y	N	X	Y	N	X	Y
1	.00	38.60	2	1.36	38.65	3	2.83	38.66	4	4.17	38.55	5	5.38	38.39
6	6.49	38.21	7	7.54	38.00	8	8.47	37.51	9	9.40	37.04	10	10.26	36.54
11	11.12	36.06	12	11.96	35.60	13	12.81	35.15	14	13.67	34.74	15	14.63	34.34
16	15.67	34.19	17	15.63	32.94	18	15.62	31.76	19	15.57	30.69	20	15.48	29.66
21	15.37	28.64	22	15.26	27.63	23	15.16	26.63	24	15.07	25.63	25	15.02	24.63
26	15.00	23.61	27	15.00	22.59	28	15.00	21.57	29	15.00	20.55	30	15.00	19.53
31	15.00	18.50	32	15.00	17.48	33	15.00	16.46	34	15.00	15.44	35	15.00	14.42
36	15.00	13.40	37	15.00	12.37	38	15.00	11.35	39	15.00	10.33	40	15.00	9.31
41	15.00	8.29	42	15.00	7.27	43	15.00	6.24	44	15.00	5.22	45	14.01	5.22
46	13.01	5.22	47	12.02	5.22	48	11.03	5.22	49	10.52	5.22	50	10.02	5.22
51	9.51	5.22	52	9.01	5.22	53	8.50	5.22	54	8.00	5.22	55	7.62	5.70
56	7.63	6.19	57	7.45	6.67	58	7.26	7.15	59	7.08	7.63	60	6.69	8.11
61	6.71	8.59	62	6.52	9.07	63	6.34	9.56	64	6.15	10.04	65	5.97	10.52
66	5.78	11.00	67	5.60	11.48	68	5.41	11.96	69	5.23	12.44	70	5.04	12.93
71	4.86	13.41	72	4.67	13.89	73	4.49	14.37	74	4.30	14.85	75	4.12	15.33
76	3.93	15.82	77	3.75	16.30	78	3.56	16.78	79	3.38	17.26	80	3.19	17.74
81	3.01	18.21	82	2.82	18.68	83	2.63	19.15	84	2.41	19.56	85	2.11	19.91
86	1.76	20.22	87	1.36	20.47	88	.93	20.62	89	.47	20.71	90	.00	20.75
91	.00	38.60												

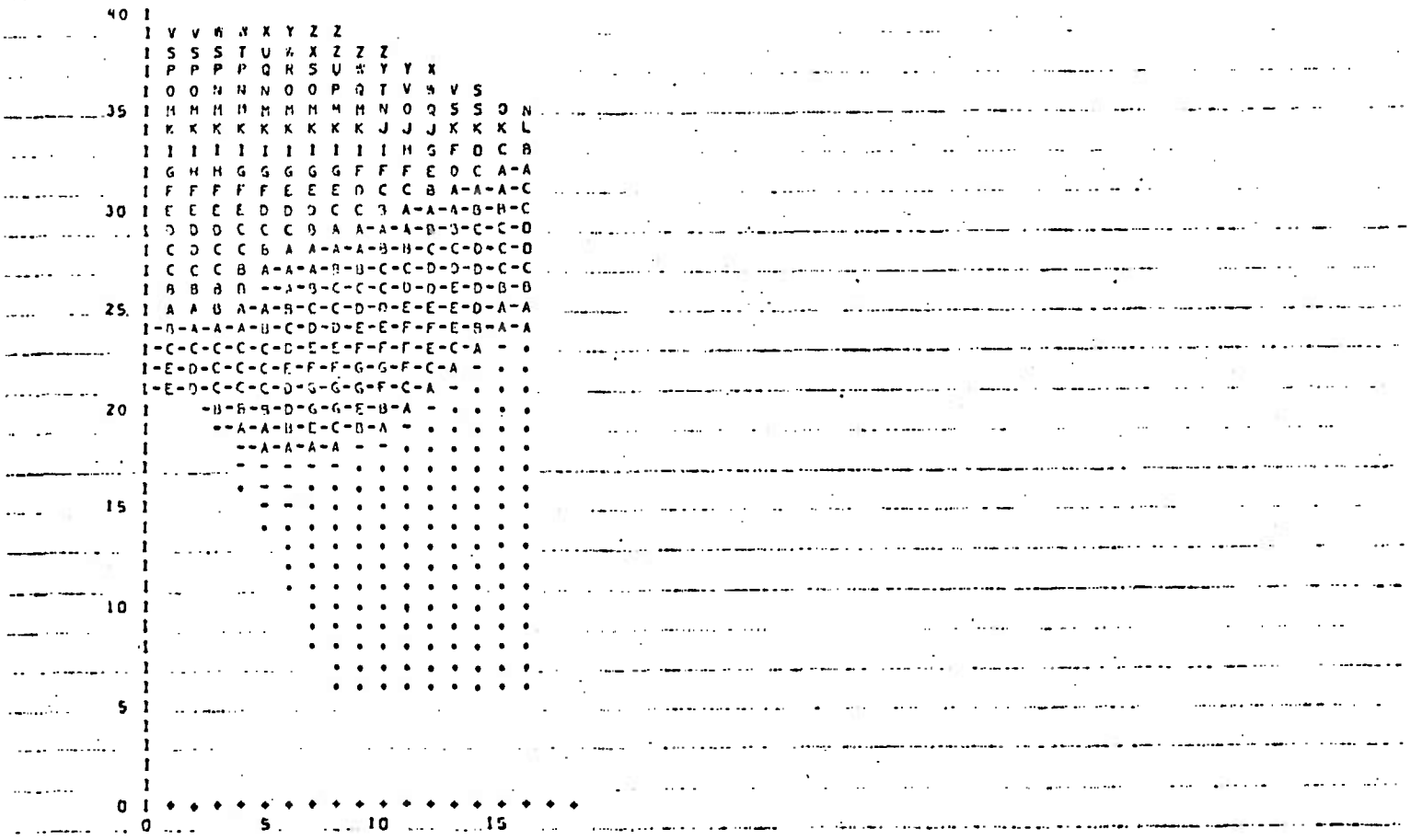
COMPRESSION CYCLE 34

SYMBOL	•	-	A	B	C	D	E	F	G	H
MAXIMUM VALUE	.190	.226	.262	.298	.334	.370	.406	.442	.478	.514
SYMBOL	I	J	K	L	M	N	O	P	Q	R
MAXIMUM VALUE	.550	.586	.622	.658	.694	.730	.766	.802	.838	.874
SYMBOL	S	T	U	V	W	X	Y	Z		
MAXIMUM VALUE	.910	.946	.982	1.018	1.054	1.090	1.126	1.162		



AXIAL VELOCITY CYCLE 34

SYMBOL	.	-	A	B	C	D	E	F	G	H
MAXIMUM VALUE	0.00	1.64+03	1.64+04	3.27+04	4.91+04	6.54+04	8.18+04	9.81+04	1.14+05	1.31+05
SYMBOL	I	J	K	L	M	N	O	P	Q	R
MAXIMUM VALUE	1.47+05	1.64+05	1.80+05	1.96+05	2.13+05	2.29+05	2.45+05	2.62+05	2.78+05	2.94+05
SYMBOL	S	T	U	V	W	X	Y	Z		
MAXIMUM VALUE	3.11+05	3.27+05	3.43+05	3.60+05	3.76+05	3.92+05	4.09+05	4.25+05		



1= 1 R(1)= 5.0000-02 DR(1)= 5.0000-02 TAU(1)= 7.8540-03

J	MFLAG	U	V	P	SIE	COMP	TMASS	SZZ	SRR	SRZ	Z
40	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2.200+00
39	211	2.4937+04	3.5065+05	4.0697+09	7.8051+09	0.0000	2.3999-04	0.0000	0.0000	0.0000	2.100+00

MAT	FRAC VOL	RHO	SIE	COMP	MASS
2	.000	0.0000	0.0000	0.0000	0.0000
20	1.000	3.0556-01	7.8051+09	1.7796-01	2.3999-04

RHO(NVOID,M)= 1.0

J	MFLAG	U	V	P	SIE	COMP	TMASS	SZZ	SRR	SRZ	Z
38	2	2.1156+04	3.0310+05	4.1611+09	8.2184+09	2.5587-01	1.7252-04	0.0000	0.0000	0.0000	2.000+00
37	2	1.5582+04	2.5627+05	7.4725+09	8.6856+09	2.9364-01	1.9799-04	0.0000	0.0000	0.0000	1.950+00
36	2	1.1289+04	2.2907+05	1.1073+10	1.0601+10	3.5650-01	2.4038-04	0.0000	0.0000	0.0000	1.900+00
35	2	6.8151+03	2.0160+05	1.5667+10	1.2716+10	4.2052-01	2.8354-04	0.0000	0.0000	0.0000	1.850+00
34	2	3.2981+03	1.7133+05	2.0634+10	1.4730+10	4.7811-01	3.2238-04	0.0000	0.0000	0.0000	1.800+00
33	2	1.5957+03	1.4019+05	2.5641+10	1.6627+10	5.2635-01	3.5490-04	0.0000	0.0000	0.0000	1.750+00
32	2	1.4313+03	1.1101+05	3.1251+10	1.8584+10	5.7395-01	3.8699-04	0.0000	0.0000	0.0000	1.700+00
31	2	2.8557+03	8.7297+04	3.7138+10	2.0922+10	6.2068-01	4.1850-04	0.0000	0.0000	0.0000	1.650+00
30	2	3.3965+03	6.8180+04	4.4402+10	2.2839+10	6.6354-01	4.4740-04	0.0000	0.0000	0.0000	1.600+00
29	2	6.5056+03	5.4355+04	5.1187+10	2.4898+10	7.0160-01	4.7312-04	0.0000	0.0000	0.0000	1.550+00
28	2	7.1669+03	4.8238+04	6.3108+10	2.8416+10	7.5801-01	5.1110-04	0.0000	0.0000	0.0000	1.500+00
27	2	1.2817+04	3.7565+04	7.1125+10	3.0838+10	7.8720-01	5.3078-04	0.0000	0.0000	0.0000	1.450+00
26	2	8.8119+03	2.0695+04	7.6977+10	3.2421+10	8.1038-01	5.4641-04	0.0000	0.0000	0.0000	1.400+00
25	2	7.2774+03	3.6165+03	7.5555+10	3.2040+10	8.0485-01	5.4264-04	0.0000	0.0000	0.0000	1.350+00
24	145	-1.9491+03	-1.9777+04	9.9120+10	7.8538+09	0.0000	1.7822-03	0.0000	0.0000	0.0000	1.300+00

MAT	FRAC VOL	RHO	SIE	COMP	MASS
2	.386	9.5024+00	0.0000	1.0677+00	1.4419-03
20	.614	1.4121+00	4.1134+10	8.2295-01	3.4027-04

RHO(NVOID,M)= .0

J	MFLAG	U	V	P	SIE	COMP	TMASS	SZZ	SRR	SRZ	Z
23	1	-2.7221+03	-4.1183+04	7.7501+10	4.1029+08	1.0484+00	3.6642-03	0.0000	0.0000	0.0000	1.250+00
22	1	-6.7718+03	-6.7797+04	1.2359+11	3.3253+08	1.0793+00	3.7723-03	0.0000	0.0000	0.0000	1.200+00
21	175	-3.6645+03	-6.6801+04	0.0000	3.4300+08	0.0000	1.2321-03	0.0000	0.0000	0.0000	1.150+00

MAT	FRAC VOL	RHO	SIE	COMP	MASS
2	.337	9.3057+00	3.4300+08	1.0456+00	1.2321-03
20	.000	0.0000	0.0000	0.0000	0.0000

RHO(NVOID,M)= 1.0

J	MFLAG	U	V	P	SIE	COMP	TMASS	SZZ	SRR	SRZ	Z
20	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.100+00
19	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.050+00
18	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.000+00
17	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	9.500-01

8.4 RESTARTING PROBLEMS

During the calculation, BRLSC periodically writes on a tape or drum file the problem parameters and the current state of the material in each cell. By reading this file and a few input cards, the code can "restart" and continue a calculation from an intermediate point.

The three cards that must be included in a restart deck are as follows:

1. the heading card
2. the restart card
3. the last card

The heading card can contain any alphanumeric symbols between columns 2 and 72. The "restart" card defines the four variables described below.

Variable Name	Columns	Definition
PK(1)	8-16	Problem number.
PK(2)	17-25	Restart cycle number.
PK(3)	26-34	Restart flag. =-1. prints long edit of restart cycle =-2. prints short edit of restart cycle.
PK(4)	35-43	Number of material packages in the problem (excluding the void package).

This restart card is read by CARDS and columns 1 through 7 are punched as follows

1	2	3	4	5	6	7	(Columns)
1			1	5	1	4	

which indicate there are four words defined by the card, the first one stored in the 151st location of blank common.

The last card defines TSTOP, the time to stop the calculation. This must be the last card of the restart cycle. The TSTOP card is punched as described above for a setup deck, e.g.,

1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	(Columns)
1				5	0	1	1.	0				-	0	6	

Many problem parameters stored in blank common can be redefined when restarting at an intermediate point in the calculation. For example, the number of times PH3 is subcycled, the frequency of printing, or the round-off epsilon can be changed by including in the restart deck cards that redefine these variables. These extra cards must be added between the "restart" card and the last card, i.e., between the two cards that have a "1" in column 1. All cards except the heading card of the restart deck are read by the CARDS subroutine with the format described in Section 8.3.2.

Examples of Restart Decks

The three cards listed below could be used to restart a problem from cycle 100 and run until 3 μsec. There are two materials in the problem (Mode 1) and a short print is desired on the restart cycle.

SHAPED CHARGE TEST PROBLEM 11.11

1	151	4	11.11	100.0	-2.0	2.0
1	50	1	3.0 -06			

The cards listed below could be used to restart a problem from Cycle 100 and run to Cycle 200. There is only one material in the problem (Mode 2 or 3) and a long print is desired on the restart cycle. The print material will also be changed so that a long edit print, with symbolic maps, will be made every 25 cycles.

SHAPED CHARGE TEST PROBLEM 22.22

1	151	4	22.22	100.0	-1.0	1.0
2	5	1	1.0			
2	7	1	200.			
2	42	1	1.0			
2	49	1	25.0			
1	50	1	0.			

8.5 DICTIONARY OF IMPORTANT VARIABLES

This section includes a description of the use, units, dimensions, and locations of all important variables in named or blank commons and some variables local to the subroutines.

Location

(NAME)	Variable is local to subroutine NAME.
NAME	Variable is in common block NAME.
B.C.	The variable is in Blank Common or equivalenced to a variable in Blank Common.
=Z(N)	The variable is equivalenced to Z(N), the first array in Blank Common. These variables are usually used in setting up and restarting problems.

Dimension

IDX	Number of cells in radial direction	(=40)
JDX	Number of cells in axial direction	(=120)
NMX	Number of material packages	(=2)
MDX	Number of mixed cells	(=400)
NTPMX	Number of tracers per package	(=300)
IDXX	IDX+1	(=41)
JDXX	JDX+1	(=121)
NMXX	NMX+1	(=3)
JDX2	2·JDX	(=240)
KDX	IDX·JDX+2	(=4802)
JDXP	10·NMX+JDX2	(=260)
MDNMX	NMXX·MDX+1	(=1201)
KDX4	(IDX/2+1)·(JDX/2+1)	(=1281)
KDXP	MAX[KDX,NMX·(JDX+5), 2·NMXX·MDX]	(=4802)

Variable Name	Location	Dimension	Units	Definition
AIX	B.C.	(KDX)	ergs/g	Specific internal energy in a cell. (IMAX by JMAX array.)
ALE	(MAP)	(41)	--	This array has alphabetic characteris for positive values in the density, velocity and energy maps. Defined in a DATA statement.
AMDM	B.C.	(NMX)	--	INPUT parameter. A material i with compression > $AMDM_i$ is considered solid. Usual value: 0.95 to 0.99. Used in CDT in testing whether to allow negative pressures (tensions) in pure cells. Used in PH3 to calculated SOLID = AMDM * RHOZ, which determines whether material stresses are nonzero.
AMMP	(PH2)	--	g	Mass transported across right boundary of a cell. (See Appendix B)
AMMU	(PH2)	--	cm-g/sec	Radial momentum transported across the bottom boundary of a cell. (See Appendix B)
AMMV	(PH2)	--	cm-g/sec	Axial momentum transported across the bottom boundary of a cell. (See Appendix B)
AMPY	(PH2)	--	g	Mass transported across top boundary of a cell. (See Appendix B)
AMUR	(PH2)	--	cm-g/sec	Radial momentum transported across right boundary of a cell. (See Appendix B)
AMUT	(PH2)	--	cm-g/sec	Radial momentum transported across top boundary of a cell. (See Appendix B)
AMVR	(PH2)	--	cm-g/sec	Axial momentum transported across top boundary of a cell. (See Appendix B)
AMX	B.C.	(KDX)	g	Total mass in a cell. (IMAX by JMAX array)
BBAR	=Z(149)	--	--	Used in CDT. An INPUT parameter used in local sound-speed calculation for all materials other than a polytropic gas. (Local sound-speed for material i in cell K is approximated as $(C_{Gi}) = BBAR \cdot \sqrt{P(K)}$, where the coefficient B is obtained by determining a typical slope for the isentropes in Ref. 3 and using the relation $C = V\sqrt{-dP/dV}$ to evaluate B at a particular point.
BBOUND	=Z(74)	--	ergs	Calculated in PH3. Printed in EDIT under "Elastic Plastic Work." Total work done by the elastic and plastic stresses.
BOTM	=Z(39)	--	g	Calculated in PH2. Printed in EDIT. Total mass transported across bottom of grid.

Variable Name	Location	Dimension	Units	Definition
BOTMU	=Z(64)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total radial-momentum transported across bottom of grid.
BOTMV	=Z(40)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total axial-momentum transported across bottom of grid.
CNAUT	MXCELL	(30)	cm/sec	Used in CDT. Approximate sound-speed of nineteen materials defined in a DATA statement in BLOCK. $C_{0i} = \sqrt{\frac{ESCAPA_i}{RHOZ_i}} = \sqrt{A_i/\rho_{0i}}$.
CVIS	=Z(27)	--	--	INPUT parameter. Used to describe the bottom boundary-condition in PH1, PH2 and PH3. Bottom boundary is transmittive when CVIS = -1., reflective when CVIS = 0.
CYC	B.C.	--	--	Defined in INFACE. Used in FLUX to define flux terms of cells that become mixed after first subcycle of INFACE.
CYCLE	=Z(2)	--	--	Used in INPUT, SETUP, CDT, EDIT. Cycle number (an integer value in floating point form).
CYCMX	=Z(69)	--	--	INPUT parameter. Equals number of passes through INFACE on each cycle. Suggested minimum of 2 and maximum of 8. Used to minimize transport noise near interfaces.
CYCPH3	=Z(70)	--	--	INPUT parameter. Number of times to subcycle PH3. If CYCPH3 $\leq$ 0, PH3 is omitted.
CZERO	B.C.	(NMX)	dynes/cm^2	Value of Y_0 for yield strength calculation. Defined by input cards for each material package in the grid. Used in STRNG. (See STRENG)
DDX	B.C.	(IDXX)	cm	An array equivalenced to the DX array such that DDX(1) = DX(0).
DDY	B.C.	(JDXX)	cm	An array equivalenced to the DY array such that DDY(1) = DY(0).
DELEB	(PH2)	--	ergs	Total energy associated with mass transported across bottom boundary of a cell. (See Appendix B)
DELET	(PH2)	--	ergs	Total energy associated with mass transported across top boundary of cell. (See Appendix B)
DELI	(PH1, PH2)	--	ergs/g	Change of specific internal energy of a cell.

Variable Name	Location	Dimension	Units	Definition
DELM	(PH2)	--	g	Total change in mass of a cell.
DELU	(PH1, PH2)	--	cm/sec	Change of radial velocity of a cell.
DELV	(PH1, PH2)	--	cm/sec	Change of axial velocity of a cell.
DMIN	=Z(24)	--	--	INPUT parameter. Allowable relative error in energy sum. When relative error is > DMIN, calculation is terminated. The energy error is computed in EDIT. If everything is working right you should be able to use 10^{-5} for DMIN.
DPDR	B.C.	--	ergs/g	Used in CDT when iterating for pressures. Computed in EQST or EOSXPL. $=(\partial P/\partial \rho)_E$
DT	=Z(3)	--	sec	Time step. Calculated in CDT.
DTFACT	(PH3)	--	--	Factor used in calculating a variable time step when subcycling the PH1 and PH3 calculation.
DTFIX	=Z(143)	--	sec	INPUT parameter. Used in CDT. If DTFIX.GT.DTMIN, then DT=min(DT,DTFIX). Used to run with a constant time step.
DTMIN	=Z(144)	--	sec	INPUT parameter. Minimum time step; used in CDT. After STAB = FINAL, if DT < DTMIN execution is stopped.
DTNA	=Z(26)	--	sec	DT from previous time cycle. Used in INPUT, CDT, and EDIT.
DTSTR	Local	--	sec	Computed in PH1. Time step for PH1 and PH3 subcycles.
DX	B.C.	(IDX)	cm	The radial-dimension of cells. Equivalenced to DDX such that DDX(1) = DX(0).
DXF	=Z(136)	--	cm	An INPUT parameter used to calculate the DX array if the radial dimension of the cells is uniform.
DY	B.C.	(JDX)	cm	The axial-dimension of cells. Equivalenced to DDY so that DDY(1) = DY(0).
DYF	=Z(137)	--	cm	An INPUT parameter used to calculate the DY array if the axial dimension of the cells is uniform.
EAMMP	(PH2)	--	ergs/g	Specific internal energy of mass transported across the right edge of cell.
EAMPY	(PH2)	--	ergs/g	Specific internal energy of mass transported across top of cell.

Variable Name	Location	Dimension	Units	Definition
ECK	=Z(76)	--	--	Used in EDIT. Relative error in energy sum: $\left(\sum_k E_k - ETH\right)/ETH$; where E_k is total energy in cell K. If |ECK| > DMIN, execution is stopped.
EMIN	=Z(85)	--	ergs/g	INPUT parameter. Mininum specific internal energy of an ideal gas or explosive to be used in the pressure iteration in CDT. Usually EMIN = 10^0.
EMOB	=Z(150)	--	ergs	Calculated in PH2. Printed in EDIT. Energy transported across bottom of mesh .
EMOR	=Z(135)	--	ergs	Calculated in PH2. Printed in EDIT. Energy transported across right side of mesh.
EMOT	=Z(146)	--	ergs	Calculated in PH2. Printed in EDIT. Energy transported across top of mesh.
ENERGY	B.C.	--	ergs/g	Defined in CDT as specific internal energy of a material. Used in EQST and EOSXPL where P = f(ENERGY,RHOW).
EOB	=Z(134)	--	ergs	Calculated in PH1. Printed in EDIT. Energy change due to work done at bottom boundary of grid.
EOR	=Z(132)	--	ergs	Calculated in PH1. Printed in EDIT. Energy change due to work done at right boundary of grid.
EOT	=Z(133)	--	ergs	Calculated in PH1. Printed in EDIT. Energy change due to work done at top boundary or grid.
ERDUMP	B.C.	--	--	Used in EDIT and ERROR. Flags EDIT to do only a tape dump on an error exit.
ERR	(PH3)	(3, JDX)	1/sec	Used in PH3. Radial component of the instantaneous strain-rate deviators.
ERZ	(PH3)	(3, JDX)	1/sec	Used in PH3. Shear component of the instantaneous strain-rate deviators.
ESA	(EQST)	(30)		Defined in DATA Statement. Values of "a" in equation of state for 19 materials. [=(γ-1) when using perfect gas equation of state.]
ESALPH	(EQST)	(30)		Defined in DATA Statement. Values of "α" in equation of state for 19 materials.
ESB	(EQST)	(30)		Defined in DATA Statement. Values of "b" in equation of state for 19 materials.

Variable Name	Location	Dimension	Units	Definition
ESBETA	(EQST)	(30)		Defined in DATA Statement. Values of "B" in equation of state for 19 materials.
ESCAPA	(EQST)	(30)	dynes/cm^2	Defined in DATA Statement. Values of "A" in equation of state for 19 materials.
ESCAPB	(EQST)	(30)	dynes/cm^2	Defined in DATA Statement. Values of "B" in equation of state for 19 materials.
ESES	(EQST)	(30)	ergs/g	Defined in DATA Statement. Values of "E_s" in equation of state for 19 materials.
ESESP	(EQST)	(30)	ergs/g	Defined in DATA Statement. Values of "E_s'" in equation of state for 19 materials.
ESEZ	(EQST)	(30)	ergs/g	Defined in DATA Statement. Values of "E_0" in equation of state for 19 materials.
ETH	=Z(13)	--	ergs	Theoretical value of total energy in the mesh. Calculated in SETUP initially; updated in APLYPR, PH1, PH2 and RMVMAT.
EVAPEN	=Z(101)	--	ergs	Calculated in PH2 and CDT. Printed in EDIT. Sum of energy lost through "evaporation" of mass left in cells due to round-off error. Adjusted in CDT when "evaporating" isolated cells. Initialized in SETUP.
EVAPM	=Z(100)	--	g	Calculated in PH2 and CDT. Printed in EDIT. Sum of mass lost through "evaporation". See EVAPEN.
EVAPMU	=Z(102)	--	cm-g/sec	Calculated in PH2 and CDT. Printed in EDIT. Sum of radial momenta lost through "evaporation". See EVAPEN.
EVAPMV	=Z(103)	--	cm-g/sec	Calculated in PH2 and CDT. Sum of axial momenta lost through "evaporation". See EVAPEN.
EZPH2	=Z(104)	--	ergs/g	Sum of specific internal energy fluxes that are less than UMIN~ and are set to zero in PH2. Printed in EDIT.
EZZ	(PH3)	(3, JDX)	1/sec	Used in PH3. Axial component of the instantaneous strain-rate deviators.
FINAL	=Z(113)	--	--	INPUT parameter. Maximum value of stability fraction (STAB). If FINAL = 0; the stability fraction will be constant. Used in CDT.
FLEFT	(PH2)	(JDX)	cm-g/sec	Radial momentum of mass transported across left side of cell. Equivalenced to UL array. (See Appendix B)
FRACRT	B.C.	(MDNMX)	cm^2	The fractional area of the right cell boundary associated with a given material in a mixed cell. Used to compute mass flux of that material.

Variable Name	Location	Dimension	Units	Definition
FRACTP	B.C.	(MDNMX)	cm^2	The fractional area of the top cell boundary associated with a given material in a mixed cell. Used to compute mass flux of that material.
GAMC	(PH2)	(JDX)	g	Mass transported across left side of cell. Equivalenced to PL array. (See Appendix B)
GAMMA	=Z(62)	--	--	Defined during SETUP. GAMMA = ESA+1 in ideal gas or explosive equation of state. Used in PH1 to partition energy in mixed cells.
I	=Z(88)	--	--	Used in most subroutines as index in radial direction.
ICSTOP	=Z(7)	--	--	INPUT parameter. Used in EDIT. Execution stops on ICSTOP cycle when stopping on a specified cycle rather than time.
IGM	=Z(21)	--	--	INPUT parameter. If IGM=0, problems are run using cylindrical geometry, if IGM=1, rectangular geometry.
IMAX	=Z(33)	--	--	INPUT parameter. Number of columns in mesh.
IMAXA	=Z(34)	--	--	IMAX + 1.
INTER	=Z(87)	--	--	INPUT parameter. On print cycle if INTER ≠ 0, EDIT will print after CDT and PH1. If INTER = 7, energy totals are printed in PH2 in addition to the extra EDIT prints.
IPCYCL	=Z(49)	--	--	INPUT parameter. Used in EDIT. The number of cycles between EDIT prints when editing on cycles rather than time.
IPR	=Z(15)	--	--	Maximum number of iterations to be performed by CDT to achieve pressure equilibration between materials in mixed cells.
IVARDX	=Z(83)	--	--	When IVARDX = 1, radial dimension of cells is variable.
IVARDY	=Z(54)	--	--	When IVARDY = 1, the axial dimension of cells is variable.
I1	=Z(47)	--	--	I1 is initialized in SETUP and is used to limit calculation in the radial direction to an "active mesh". Beyond I1 nothing is yet disturbed from the initial conditions. I1 is specified initially as (2 + the column-number of the last column in which there is a non-zero velocity or internal energy). I1 is increased automatically as inactive cells become active. However, I1 is never larger than IMAX.

Variable Name	Location	Dimension	Units	Definition
I2	=Z(48)	--	--	Initialized in SETUP. Like I1 but for axial disturbance limit.
I3	B.C.	--	--	Used in EDIT as a flag for "short" or "long" prints. I3 = number of columns of grid whose U, V, P, AIX, etc. are listed.
J	=Z(89)	--	--	Used as row-index in most subroutines.
JMAX	=Z(35)	--	--	INPUT parameter. Number of rows in the grid.
JMAXA	=Z(36)	--	--	Calculated in SETUP, (JMAX + 1).
K	=Z(90)	--	--	Used as cell-index in all subroutines. K = (J-1)*IMAX + I + 1.
KA	B.C.	--	--	Used as cell-index for cell above cell K.
KB	B.C.	--	--	Used as cell-index for cell below cell K.
KL	B.C.	--	--	Used as cell-index for cell to left of cell K.
KMAX	=Z(37)	--	--	Calculated in SETUP (=IMAX*JMAX + 1). K-index of last cell in grid.
KMAXA	=Z(38)	--	--	Calculated in SETUP (KMAX + 1).
KR	B.C.	--	--	Used as cell index for cell to right of cell K.
KSPACE	(EDIT)	--	--	Used for spacing printed output.
KUNITR	=Z(14)	--	--	Unit number of tape read by INPUT.
KUNITW	=Z(17)	--	--	Unit number of tape written on by SETUP and EDIT.
M	=Z(91)	--	--	Usually used as an index for cell K in the mixed cell arrays. M = MFLAG(K)-100.
MA	B.C.	--	--	Usually value of MFLAG for cell above cell K.
MAPS	=Z(42)	--	--	INPUT parameter that determines the printing of symbolic maps on EDIT cycles. If MAPS = 0, maps are not printed; if MAPS = 1, they are printed.
MAT	B.C.	(30)	--	Material code number for the liner. MAT(1) = 3 indicates the material in package one is iron. See list in Section 2.3 of this report or comments in listing of EQST subroutine.
MATXPL	=Z(106)	--	--	If MAT(2)=20, package two is an ideal gas (explosive). MATXPL then identifies the explosive.
MFK	B.C.	--	--	Usually = MFLAG(K).

Variable Name	Location	Dimension	Units	Definition
MFLAG	B.C.	(KDX)	--	Flag for each cell that indicates whether it is pure or mixed. If MFLAG(K) < 100 cell is pure. If MFLAG(K) > 100 cell is mixed and flag gives storage location in mixed cell arrays for cell K (see Appendix C).
MO	B.C.	--	--	Defined in CALFRC. MFLAG(K) of cell K before it becomes mixed. Used in NEWMIX to define mixed cell variables for cell K.
MR	B.C.	--	--	Value of MFLAG for cell on right.
N	B.C.	--	--	In EQST, N is material code number transferred from CDT.
N6	=Z(56)	--	--	INPUT parameter. Used in CDT. Negative pressures are allowed in cells above J = N6.
N10	=Z(60)	--	--	Used in CDT to identify I-index of cell which controls the time step.
N11	=Z(61)	--	--	Used in CDT to identify J-index of cell which controls the time step.
NAPRND	=Z(23)	--	--	Used in APLYPR to identify the last free surface tracer describing the section of the free surface which will have a pressure force applied to it.
NAPRST	=Z(23)	--	--	Similar to NAPRST except it identifies the first tracer. NAPRST = 0 means that no pressure force is to be applied.
NC	=Z(30)	--	--	Cycle number. Set initially to -1 in input. Incremented thereafter in CDT.
NDUMP7	=Z(6)	--	--	INPUT parameter. Used in EDIT to control frequency of tape dumps. e.g., tape dump will occur on every EDIT print when NDUMP7 =1, or on every fifth EDIT print when NDUMP7 = 5.
NECYCL	=Z(77)	--	--	Defined and printed in EDIT. The cycle during which the largest relative error in the energy sum was computed.
NERR	B.C.	--	--	Used in ERROR as exit flag. Prevents ERROR from being called more than once during a single run.
NFRELP	=Z(5)	--	--	INPUT parameter. Used in EDIT to control frequency of "long" prints. A "long" print will occur with every EDIT if NFRELP = 1; with every fifth EDIT if NFRELP = 5 (see I3).
NK	B.C.	--	--	Tells which statement number of a subroutine is near the call to ERROR.

Variable Name	Location	Dimension	Units	Definition
NKDX4	=Z(117)	--	--	Number of interior tracers (XP, YP) that are in the problem.
NMAT	=Z(68)	--	--	INPUT parameter. Equals number of material packages in the problem.
NMP	B.C.	(NMXX)	--	NMP(N) is the number of interface tracers describing material package N.
NMXCLS	=Z(73)	--	--	INPUT parameter. Equals the maximum number of mixed cells that SETUP or NEWMIX can generate. This number should coincide with the dimension of variables in the MXCELL common block.
NODUMP	=Z(96)	--	--	INPUT parameter. Used in EDIT. When NODUMP = 1, no tape dumps are made except by SETUP on cycle 0. Allows user to restart a problem without writing on the restart tape.
NPRINT	B.C.	--	--	NPRINT = 1 during the cycle on which EDIT prints and checks the energy error.
NR	B.C.	--	--	Identifies which subroutine calls ERROR. Used in ERROR for printing error message.
NTCC	=Z(81)	--	--	INPUT parameter. When NTCC = 1 passive cell centered tracers are used.
NTCRSV	=Z(97)	--	--	Defined in SETUP. Used in MOVTCR to identify the tracer at the lower left hand corner of the liner.
NTPMX	=Z(78)	--	--	INPUT parameter. Equals the maximum number of tracers that SETUP will generate to circumscribe a single material package. The value of this number should not exceed the dimension of the TX and TY arrays.
NUMSCA	=Z(43)	--	--	INPUT parameter. Number of times the print interval is to be rescaled. Used in EDIT. See PRDELT for further details.
NUMSP	=Z(4)	--	--	Used in EDIT to count the number of prints (short or long) since the last tape dump.
NVOID	B.C.	--	--	Defined in INPUT: =NMAT+1, number of material packages + 1. The number of the void package if there is one.
P	B.C.	(KDXP)	dynes/cm^2	Cell pressure. (IMAX by JMAX array). Calculated in EQST. Used by PH1. [NOTE: the P-storage space is used for other information in INFACE and PH2.]
PIDY	=Z(8)	--	--	= π(3.1415927)
PL	B.C.	(JDXP)	dynes/cm^2	Used in PH1 for saving pressures on left side of cell. (Storage used for other purposes in CDT and PH2.)

Variable Name	Location	Dimension	Units	Definition
PLW	MXCELL	(NMX)	ergs	An array that stores the total work done by plastic stresses in each material package. Calculated in PHS; printed in EDIT.
PMIN	=Z(86)	--	dynes/cm^2	Used as a pressure cut-off. If the $\|P\|$ is less than PMIN, P = 0.
PRCNT	=Z(16)	--	--	Convergence requirement for equilibrating pressures in a mixed cell. If $\left(\frac{P_i - \bar{P}}{\bar{P}}\right) \leq$ PRCNT for all materials (i) in in K, materials in cell are considered to be pressure equilibrated and P(K) = $\bar{P}$.
PRDELT	=Z(45)	--	sec	INPUT parameter. Gives the initial time interval between EDIT prints. There are five parameters which control printing frequency: PRDELT, IPCYCL, PRLIM, PRFACT, and NUMSCA. If the user is printing on time (PRDELT $\neq$ 0 and IPCYCL = 0), DT will be adjusted so that a print will occur exactly every PRDELT seconds. If the user is printing on cycles (PRDELT = 0, IPCYCL $\neq$ 0), a print will occur every IPCYCL cycles. PRLIM, PRFACT and NUMSCA are used to increase the print interval. PRLIM is the time (or cycle) at which PRDELT (or PICYCL) and PRLIM are multiplied by PRFACT. The new value of PRLIM establishes the next time (or cycle) when the print interval will be rescaled. This process continues at most NUMSCA times. EXAMPLE: You wish to print every 1×10^{-8} sec until you reach 1×10^{-7} sec, then every 1×10^{-7} sec until 1×10^{-6} sec and every 1×10^{-6} sec thereafter: PRDELT = $1. \times 10^{-8}$ PRLIM = $1. \times 10^{-7}$ PRFACT = 10. NUMSCA = 2.
PRESUR	B.C.	--	dynes/cm^2	Defined in EQST: pressure = f(ρ, E). Used in CDT to define P(K) in the case of pure cells, and in the case of mixed cells to define the pressure of a material.
PRFACT	=Z(46)	--	--	INPUT parameter. Used in EDIT as a factor for rescaling PRDELT, IPCYCL and PRLIM when PRLIM-time or cycle is reached (see PRDELT). Should be > 1.
PRLIM	=Z(44)	--	--	INPUT parameter. Time or cycle at which to rescale PRDELT (or IPCYCL) and PRLIM by PRFACT (see PRDELT).
PROB	=Z(1)	--	--	INPUT parameter. Identifying problem number. Should be between 0 and 100.
PRTIME	=Z(131)	--	sec	Initially set to PRDELT in INPUT. Thereafter calculated in EDIT. When T = PRTIME, it is time to print.

Variable Name	Location	Dimension	Units	Definition
RATIO	(CDT)	--	sec	Used in calculation of DT: = DX · DY/ (DX·|V| + DY·|U|).
RELERR	(EDIT)	--	--	Used for storing and printing maximum relative error in the energy sum.
RHO	MXCELL	(NMXX,MDX)	g/cm^3	The density of materials in mixed cells. Updated in CDT and PH2. If cell K is mixed and M = MFLAG(K)-100, then RHO(1,M) is the density of material 1 in cell K. (See Appendix C)
RHOIN	B.C.	(NMX)	g/cm^3	The initial densities of material in the packages. Defined by input cards read by SETUP.
RHOW	B.C.	--	g/cm^3	Density of material. Defined in CDT and used in EQST to define pressure: P = f(ENERGY,RHOW).
RHOZ	MXCELL	(30)	g/cm^3	Defined in DATA statement in BLOCK. Normal density for 19 materials.
RMU	B.C.	(NMX)	$dynes/cm^2$	Rigidity modulus values for material packages. Defined by input cards read by SETUP. Used in PH3.
ROEPS	=Z(110)	--	--	INPUT parameter. A round-off epsilon used in calculating cutoffs of energy, velocity, pressure and mass flus.
RTIPI	=Z(28)	--	cm	Radius of tip of liner. (See YCENT) If RTIP1 < 0, liner has a pointed tip.
RTM	=Z(57)	--	g	Calculated in PH2. Printed in EDIT. Total mass lost out right side of grid.
RTMU	=Z(10)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total radial-momentum lost out right side of grid.
RTMV	=Z(58)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total axial-momentum lost out right side of grid.
SAMMP	MXCELL	(NMX,MDX)	g	The flux of materials across right boundary of mixed cells. Calculated in FLUX; used in PH2 and INFACE.
SAMPY	MXCELL	(NMX,MDX)	g	The flux of materials across the top boundary of mixed cells. Calculated in FLUX; used in PH2 and INFACE.
SDT	B.C.	--	sec	Defined in INFACE: = DT/CYCMX. Time step for each subcycle of INFACE.
SIE	MXCELL	(NMX,MDX)	ergs/g	The specific internal energy of materials in mixed cells. If cell K is mixed and M = MFLAG(K)-100, then SIE(1,M) is the specific internal energy of material one in cell K (see XMASS, RHO).

Variable Name	Location	Dimension	Units	Definition
SIENEW	(PH2)	--	ergs/g	New value of specific internal energy.
SIGC	B.C.	(JDX)	ergs	Used in PH2 for internal energy of mass transported across left side of cell. (See Appendix B)
SIGMU	(PH2)	--	cm-g/sec	Total change in radial momentum of a cell.
SIGMV	(PH2)	--	cm-g/sec	Total change in axial momentum of a cell.
SLOPLN	=Z(31)	--	--	Slope of inside surface of liner (see YTOPI).
SOLID	(STRNG)	--	g/cm^3	= $RHOZ_i$ * $AMDM_i$. In PH3, if RHO_i < SOLID for one material, i, in cell K, stresses of cell K are set to zero.
SRATIO	(CDT)	--	sec	Used to calculate DT. Smallest value of RATIO found in the active grid.
SRR	(PH3)	(3, JDX)	$dynes/cm^2$	Temporary storage for cell centered deviatoric normal stress in the radial direction. See STRSRR.
SRZ	(PH3)	(3, JDX)	$dynes/cm^2$	Similar to SRR but for shear stress. See STRSRZ.
SSIEN	B.C.	(NMX)	ergs/g	Initial specific internal energy of each package. Defined by input cards read in SETUP.
STAB	=Z(139)	--	--	INPUT parameter. Used in CDT. Initial value of "stability fraction" for the calculation of DT. If FINAL = 0., STAB is constant. Otherwise its value progresses from STAB to FINAL in a geometric progression. [NOTE: DT = STAB * SRATIO]
STEZ	B.C.	(NMX)	ergs/g	E_0 for each material package. Used in yield-strength calculation in STRNG. Defined by input cards read by SETUP. (See STRENG)
STK1	B.C.	(NMX)	$dynes/cm^2$	Y_1 for each material package. Used in yield-strength calculation in STRNG. Defined by input cards read by SETUP. (See STRENG)
STRENG	(STRNG)	--	$dynes/cm^2$	Yield strength of material: $STRENG = (Y_0 + Y_1 P)(1 - E/E_0)$ $\mu = \rho/\rho_0 - 1$. If STRENG ≤ 0., stresses are set to 0. If $E > E_0$, STRENG = 0 and stresses are set to 0.

Variable Name	Location	Dimension	Units	Definition
STRENG (continued)				Y_0 is CZERO, Y_1 is STK1, P is pressure of material, E is specific internal energy of material, E_0 is STEZ, ρ is density of material, ρ_0 is normal density of material.
STRSRR	ELPL	(KDX)	dynes/cm^2	The cell centered deviatoric normal stress in the radial direction (IMAX by JMAX array).
STRSRZ	ELPL	(KDX)	dynes/cm^2	The cell centered deviatoric shear stress (IMAX by JMAX array).
STRSZZ	ELPL	(KDX)	dynes/cm^2	The cell centered deviatoric normal stress in the axial direction (IMAX by JMAX array).
SUM	B.C.	--	--	Used in most routines as working storage when summing quantities.
SUME	(PH2)	--	ergs	Used in PH2. Sums energy fluxes ignored during one cycle. Used to adjust ETH, the theoretical energy total.
SZZ	(PH3)	(3,JDX)	dynes/cm^2	Similar to SRR but for axial direction. See STRSZZ.
T	=Z(84)	--	sec	Time. Initially defined in INPUT. Incremented in CDT. Adjusted in EDIT for printing and stopping at specified time values.
TAU	B.C.	(IDX)	cm^2	Initially defined in SETUP. Area of cell face: = $\pi[X(I)^2 - X(I-1)^2]$ for cylindrical problems. = X(I) - X(I-1) for rectangular problems. Used in most subroutines. See IGM.
TAUDTS	(PH1)	--	cm^2/sec	= TAU * DT.
THO3	(PH3)	--	1/sec	= $1/3\left(u_r + v_z + \frac{u}{r}\right)$.
TJMOB	=Z(98)	--	g	Total jet mass which has passed out the bottom of the grid. Computed and printed in PH2 every cycle.
TOPM	=Z(63)	--	g	Calculated in PH2. Printed in EDIT. Total mass transported across top of grid.
TOPMU	=Z(9)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total radial-momentum transported across top of grid.

Variable Name	Location	Dimension	Units	Definition
TOPMV	=Z(66)	--	cm-g/sec	Calculated in PH2. Printed in EDIT. Total axial-momentum transported across top of grid.
TRIAL	(CDT)	--	cm/sec	Used in CDT. Maximum sum in the entire grid of a cell's sound-speed and largest velocity component. Printed in CDT as MAXCUV.
TSTOP	=Z(50)	--	sec	INPUT parameter. Value of T at which execution stops when stopping on time rather than cycles.
TWOPI	B.C.		--	Calculated in INPUT. = 2π.
TX	B.C.	(NMXX,NTPX)	cell	X-coordinates of tracer particles circumscribing the material packages.
TY	B.C.	(NMXX,NTPX)	cell	Y-coordinates of tracer particles circumscribing the material packages.
U	B.C.	(KDX)	cm/sec	Radial velocity of cell (IMAX by JMAX array).
UAMMP	(PH2)	--	cm/sec	Radial velocity of mass transported across right cell edge.
UAMPY	(PH2)	--	cm/sec	Radial velocity of mass transported across top cell edge.
UEFF	(MOVTCR)	--	cm/sec	Radial velocity of a tracer particle, computed from an area-weighted averaging scheme.
UL	(PH1)	(JDX2)	cm/sec	Radial velocity at left boundary of cell K. UL array equivalenced to the FLEFT and YMAC arrays used in PH2.
UMIN	=Z(129)	--	cm/sec	Calculated in CDT. Used as velocity cutoff in PH2: = (ZUEPS) * (sound-speed * velocity)$_{max}$.
UNxxx	=Z(xxx)	--	--	Unused Z-storage
UNEW	(PH2)	--	cm/sec	New radial velocity of cell K.
UOX	(PH3)	--	cm/sec	= $2U/(X_i + X_{i-1})$. Used to define strain rates of cell K.
URR	B.C.	--	cm/sec	Used in FLUX and PH2. Temporary storage for radial transport velocity at right boundary of cell K.
UUR	B.C.	(NMX)	cm/sec	Initial radial velocities of packages. Defined by input cards read in SETUP.
UVMAX	=Z(80)	--	cm/sec	Calculated in CDT. Maximum velocity in grid.
V	B.C.	(KDX)	cm/sec	Axial velocity of cell (IMAX by JMAX array).

Variable Name	Location	Dimension	Units	Definition
VABOVE	B.C.	--	cm/sec	Used in FLUX and PH2. Temporary storage for axial transport velocity at top boundary of cell.
VAMP	(PH2)	--	cm/sec	Axial velocity of mass transported across right edge of cell.
VAMPY	(PH2)	--	cm/sec	Axial velocity of mass moving across top edge of cell.
VBLO	(PH1)	--	cm/sec	Axial velocity at bottom boundary of cell.
VEFF	(MOVTCR)	--	cm/sec	Axial velocity of a tracer particle, computed from an area-weighted averaging scheme.
VNEW	(PH2)	--	cm/sec	New axial velocity of cell K.
VOLCOF	(PH1)	(NMX)	$g^2/sec^2\text{-}cm^4$	Used in PH1 to compute the distribution of internal energy to material in mixed cells.
VOLMAT	MXCELL	(NMX,MDX)	cm^3	Volume of material in mixed cells. = XMASS(N,M)/RHO(N,M)
VOLRT	MXCELL	(NMX,MDX)	cm^3	Volume flux of material at right boundary of cell. (See Appendix B)
VOLTP	MXCELL	(NMX,MDX)	cm^3	Volume flux at top boundary of cell (See Appendix B)
VOW	(EQST)	--	--	$= \rho_0/\rho$.
VVA	B.C.	(NMX)	cm/sec	Initial axial velocities of packages. Defined by input cards read by SETUP.
WFLAGF	=Z(51)	--	--	Used in INPUT and EDIT. Set = 1. on first cycle of run in INPUT. Triggers an EDIT print on first cycle of every run. Reset to 0. at end of EDIT.
WFLAGL	=Z(52)	--	--	Used in MAIN and EDIT. Flags last cycle. Set = 1. in EDIT. Signals BRLSC to call exit.
WPB	(PH1)	--	$dynes/cm^2$	Used in PH1 to store the interface pressures at cell edges. i.e., WPR is the interface pressure between cell K and cell KR (= K+1)
WPL	B.C.	(JDX)		
WPR	(PH1)	--		
WPT	(PH1)	--		
WSTB	(PH1)	--	$dynes/cm^2$	Used in PH1 to store the deviator shear stress at each interface of a cell.
WSTL	B.C.	(JDX)		
WSTR	(PH1)	--		
WSTT	(PH1)	--		
WS	B.C.	--	--	Used in most subroutines for local working storage.
WSA	B.C.			
WSB	B.C.			
WSC	B.C.			
WSX	B.C.			
WSY	B.C.			

Variable Name	Location	Dimension	Units	Definition
WUB	(PH1,PH3)	--	cm/sec	Used in PH1 and PH3 to store the radial components of velocity at each cell interface.
WUL	B.C.	(JDX)		
WUR	(PH1,PH3)	--		
WUT	(PH1,PH3)	--		
WVB	(PH1,PH3)	--	cm/sec	Used in PH1 and PH3 to store the axial components of velocity at each cell interface.
WVL	B.C.	(JDX)		
WVR	(PHL,PH3)	--		
WVT	(PH1,PH3)	--		
X	B.C.	(IDX)	cm	Distance from axis to outside of cell. Equivalenced to XX array such that X(0) = XX(1).
XCONI	=Z(99)	--	cm	The X-coordinate of the point at which the curved inside tip of the liner meets the straight inside section of the liner.
XIENRG	=Z(140)	--	ergs	Total internal energy. Calculated in EDIT and used for printing labels on tracer particle plots.
XKENRG	=Z(141)	--	ergs	Total kinetic energy. Calculated in EDIT and used for printing labels on tracer particle plots.
XMASS	MXCELL	(NMX,MDX)	g	The mass of materials in mixed cells (see SIE, RHO).
XMAX	=Z(18)	--	cm	= X(IMAX).
XP	TRACRS	(KDX4)	cell	X-coordinates of passive cell-centered tracer particles.
XPLCNT	=Z(108)	--	cm	The axial coordinate of the point where the detonation was initiated.
XPLDET	(EOSXPL)	(18)	cm/sec	Defined in DATA Statement. Gives detonation velocities for 18 explosives.
XPLENG	(EOSXPL)	(18)	ergs/g	Defined in DATA Statement. Values of specific detonation energy for 18 explosives.
XPLGAM	(EOSXPL)	(18)	--	Defined in DATA Statement. Values of "γ" for 18 explosives.
XPLRAD	=Z(107)	--	cm	The initial (T=0) radius of the detonation front. If a plane detonation front is used, = 0.
XPLRHO	(EOSXPL)	(18)	g/cm^3	Defined in DATA Statement. Values of initial densities for 18 explosives.
XPLVEL	=Z(109)	--	cm/sec	Velocity at which explosive package is being moved through grid. Set = VVA(2).

Variable Name	Location	Dimension	Units	Definition
XTENRG	=Z(142)	--	ergs	Total energy. Calculated in EDIT and used for printing labels on tracer particle plots.
XUM	(MAP)	(41)	--	Used in MAP. Array has negative alphabetic characters for maps. Defined in a DATA Statement.
XX	B.C.	(IDXX)	cm	Equivalenced to X array so as to make X(0) available.
Y	B.C.	(JDX)	cm	Distance from bottom of grid to top of cell. Equivalenced to YY array such that Y(0) = YY(1).
YAMC	B.C.	(JDX)	cm-g/sec	Calculated and used in PH2. Axial momentum of mass transported across left side of cell. Equivalenced to UL array. (See Appendix B)
YCENT	=Z(25)	--	cm	The tip of the line is described by: y = SLOPLN·x + YTOPI.
YMAX	(SETUP)	--	cm	= Y(JMAX).
YP	TRACRS	(KDX4)	cell	Y-coordinates of passive cell-centered tracer particles.
YY	B.C.	(JDXX)	cm	Equivalenced to Y array so as to make Y(0) available.
Z	B.C.	--	--	Storage for most of the input parameters follows Z, the first word of blank common. The "Z-array" (the first 150 words of blank common) is written on tape for restarting problems (see Appendix A).

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APPENDIX A

Z-BLOCK VARIABLES LISTED NUMERICALLY

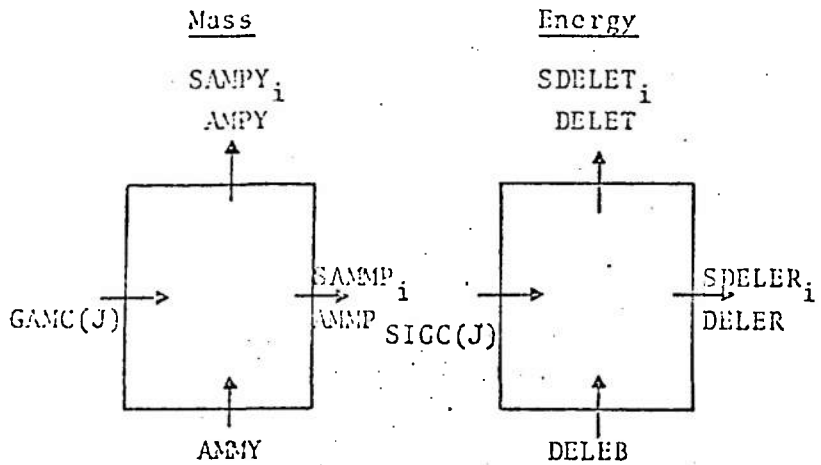
See Dictionary for meaning and use.

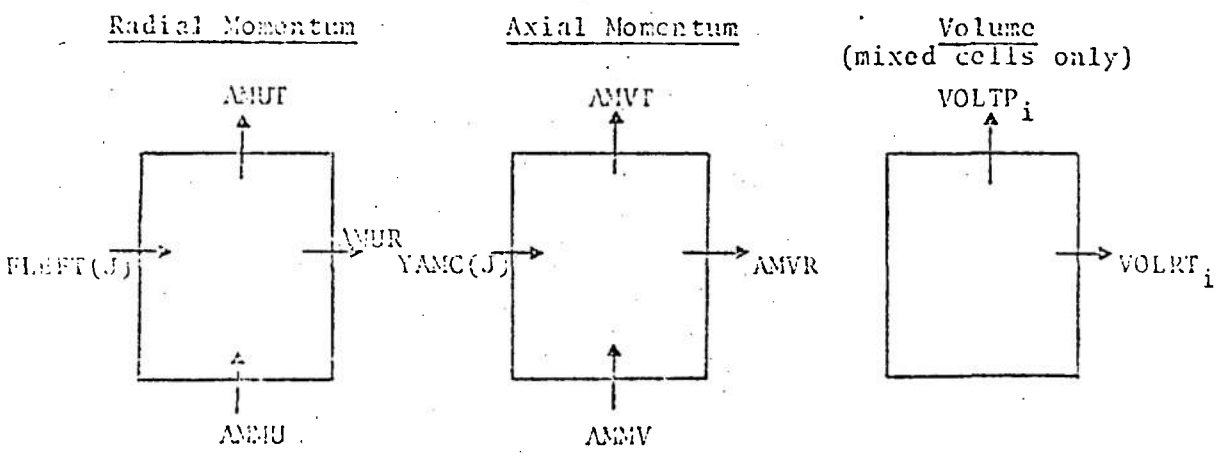
1. PROB
2. CYCLE
3. DT
4. NUMSP
5. NFRELP
6. NDUMP7
7. ICSTOP
8. PIDY
9. TOPMU
10. RTMU
11. UN11
12. NUMREZ
13. ETH
14. KUNITR
15. IPR
16. PRCNT
17. KUNITW
18. XMAX
19. NZ
20. NREZ
21. IGM
22. NAPRST
23. NAPRND
24. DMIN
25. YCENT
26. DTNA
27. CVIS
28. RTIPI
29. UN29
30. NC
31. SLOPLN
32. NRC
33. IMAX
34. IMAXA
35. JMAX
36. JMAXA
37. KMAX
38. KMAXA
39. BOTM
40. BOTMV
41. NUMSPT
42. MAPS
43. NUMSCA
44. PRLIM
45. PRDELT
46. PRFACT
47. I1
48. I2
49. IPCYCL
R50. TSTOP
51. WFLAGF
52. WFLAGL
53. UN53
54. IVARDY
55. VT
56. N6
57. RTM
58. RTMV
59. UN59
60. N10
61. N11
62. GAMMA
63. TOPM
64. BOTMU
65. UN65
66. TOPMV
67. NSIDES
68. NMAT
69. CYCMX
70. CYCPH3
71. REZFCT
72. NTRACR
73. NMXCLS
74. BBOUND
75. UN75
76. ECK
77. NECYCL
78. NTPMX
79. UN79
80. UVMAX
81. NTCC
82. UN82
83. IVARDX
84. T
85. EMIN
86. PMIN
87. INTER

88. I
89. J
90. K
91. M
92. N
93. UN93
94. YTOPI
95. REZ
96. NODUMP
97. NTCRSV
98. TJMOB
99. XCONI
100. EVAPM
101. EVAPEN
102. EVAPMU
103. EVAPMV
104. EZPII2
105. UN105
106. MATXPL
107. XPLRAD
108. XPLCNT
109. XPLVEL
110. ROEPS
111. UN111
112. UN112
113. FINAL
114. UN114
115. MBBB
116. MBB
117. NKDX4
118. NADD
119. MINX
120. MAXX
121. MINY
122. MAXY
123. IEXTX
124. JEXTY
125. UN125
126. UN126
127. SS1
128. SS2
129. UMIN
130. SS4
131. PRTIME
132. EOR
133. EOT
134. EOB
135. EMOR
136. DXF
137. DYF
138. UN138
139. STAB
140. XIENRG
141. XKENRG
142. XTENRG
143. DTFIX
144. DTMIN
145. UN145
146. EMOT
147. JCENTR
148. RADIUS
149. BBAR
150. EMOB = 0 [Last card of SETUP input deck. Not included when restarting from tape.]
151. PK(1) should be the same as PROB, problem number.
152. PK(2), the restart cycle.
153. PK(3): when = -1., program will restart from tape and do a "long" EDIT prints of the pickup cycle. When = -2., program will restart from tape and do a "short" EDIT print of the pickup cycle.

APPENDIX B

VARIABLES USED IN TRANSPORT ACROSS CELL BOUNDARIES





APPENDIX C

FLAGS AND CONVENTIONS GOVERNING INTERFACE CELLS AND CELLS CONTAINING EXPLOSIVES

Statements	Meaning
RHO(1,M) = -1.0	The M location in mixed cell arrays (XMASS, RHO, SIE, FRACTP, FRACRT, VOLMAT, VOLRT, VOLTP, SAMMP, SAMPY) is not in use.
NVOID = NMAT + 1	NVOID, the number of the "void" package, is one more than the number of material packages.
M = MFLAG(K)-100 RHO(NVOID,M) = 1.0	Cell K contains the free surface interface.
MFLAG(K) = 0	Cell K is empty and is not cut by an interface, i.e., it is a void cell.
0 < MFLAG(K) < 100	Cell K is nonempty and pure, ie., does not contain an interface.
MFLAG(K) = 2	Cell K is completely inside package 2 boundary and contains only material of package 2.
MFLAG(K) > 100	Cell K is mixed, i.e., contains at least one interface. M = FLAG(K)-100 gives location of quantities in mixed cell arrays for cell K.
MFLAG(K) < 0	(a) During INFACE or PH2, cell K was mixed, but is no longer cut by an interface and will be reflagged at the end of PH2. (b) During CDT or PH1, cell K has an artificial driving force acting on it. Pressures are set by APLYPR.

Statements	Meaning
MAT(1) = 3	The material code number of package is 3. The list in EQST indicates that code number 3 corresponds to iron.
M = MFLAG(K)-100 RHO(N,M) = 0.	The interface of package N does not cut cell K. Material of package N will not be transported into cell K.
M = MFLAG(K)-100 RHO(N,M) > 0 XMASS(N,M) = 0.	Package N interface cuts cell K, but cell K does not yet contain any material of package N.
M = MFLAG(K)-100 RHO(N,M) = 0. XMASS(N,M) > 0.	Package N interface has left cell K and the material of package N [XMASS(N,M)] should be completely evacuated on this cycle.
MAT(2) = 20	The material of package 2 is an Ideal Gas (MATXPL=0) or an explosive (MATXPL≠0) and is given special treatment in the pressure calculation, sound speed calculation and the strength phase of the code.
NAPRST = 0	No pressure boundary condition is being used.
NAPRST > 0 NMAT = 1	A pressure boundary condition is being applied along a section of the free surface defined by free surface tracers. [TX(NVOID, NAPRST), TY(NVOID, NAPRST) through TX(NVOID,NAPRND), TY(NVOID,NAPRND)].
MATXPL > 0 MAT(2) = 20	Material package 2 is an explosive detonating with a plane detonation front.

Statements	Meaning
MATXPL < 0 MAT(2) = 20	Material package 2 is an explosive detonating with a curved detonation front.

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